SUPPLEMENTAL AERATION SYSTEM DESIGN

FOR

THE HOUSTON SHIP CHANNEL

by

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ABSTRACT

The oxygen demand on the Houston Ship Channel exceeds its natural assimilative capacity. Dissolved oxygen (DO) is depleted so that warm weather and low flow commonly produce zero DO concentration in the upper 14 miles of the channel. This study develops and demonstrates a technique for designing an in-channel supplemental aeration system that might be considered as an alternative to advanced waste treatment.

A mathematical model is used to calculate the capacity of supplemental aeration systems capable of producing 2 and 4 milligrams per liter (mg/l) DO in the channel under critical conditions, and to locate aeration equipment for maximum efficiency. Accurate simulation of oxygen dynamics is critical, and extensive effort is made in modeling oxygen sources and sinks. Model verification is conducted under both steady state and dynamic conditions.

A general system design consisting of required oxygen transfer capacities under critical and average conditions, and site locations is developed. Sidestream oxygenation, diffused aeration, diffused oxygen, and surface aeration systems are evaluated for their ability to meet the requirements of the general design, for their economic desirability, and for their physical feasibility. Sidestream oxygenation is selected for preliminary design. The 1975 cost of supplemental aeration by side-stream oxygenation is estimated at 2.0 to 2.5 cents per pound of oxygen transferred.

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CHAPTER I

INTRODUCTION

The Houston Ship Channel receives many types of pollutants from the domestic and industrial community in the Houston area. The best known and most noticeable result of this pollution is depleted dissolved oxygen (DO) concentration. The low DO problem in the channel has been well documented with readings often dropping to zero DO.[1,2,3,4] The Texas Water Quality Board (T.W.Q.B.), with Environmental Protection Agency (E.P.A.) approval, has specified the following minimum criteria for DO in the ship channel: 1) 1.5 mg/l in the turning basin area, 2) 2 mg/l from the turning basin to the San Jacinto Monument, and 3) 4 mg/l from the monument to Morgan's Point.[5]

The first step to meeting T.W.Q.B. criteria is improved treatment of waste effluents. Significant reductions were made in the five-day biochemical oxygen demand (BOD_5) placed in the channel from 1968 to 1970 when industries began installing secondary treatment plants, but the load has since stabilized at about 150,000 pounds of BOD_5 per day.[6] The natural assimilative capacity of the channel is estimated at only 20,000 to 50,000 pounds of BOD_5 per day[6] and, therefore, the channel remains out of compliance with T.W.Q.B. DO criteria.[7]

Theoretically, current technology can remove almost 100 percent of the oxygen-demanding pollutants from waste effluents; however, in-channel aeration may be more cost-effective. Treatment of domestic wastes costs an average of 20.8 cents per pound of BOD_5 at the 99 percent removal level and the cost of the increment between 98 and 99 percent removal was 1.74 dollars per pound of BOD_5 in 1973.[6] Industrial wastes are generally even more expensive to treat. The cost of supplemental aeration was estimated to be only 1.4 to 5 cents per pound of oxygen transferred in 1970[8,9], making supplemental aeration a possible alternative to high-level waste treatment.

Several agencies and water quality experts have shown interest in aerating the ship channel. The Environmental Engineering Division of Texas A&M University and the Gulf Coast Waste Disposal Authority have jointly proposed the use of supplemental aeration in the ship channel[6], but only preliminary feasibility investigations have been undertaken. The Texas Water Quality Board has also shown interest in supplemental aeration and, through its consultants, has briefly examined the effects of reaeration.[10,11] Professor W. Wesley Eckenfelder, a respected authority on water quality, speaking at the Texas Water Quality Board Waste Load Evaluation Hearing for the Houston Ship Channel argued that supplemental aeration is less expensive than high-level treatment of industrial wastes and should be considered as an alternate.[12]

The ship channel is a unique aquatic system which poses questions in aeration system selection and design that are as yet unanswered. In order for governing agencies to objectively consider the alternative of supplemental aeration these questions must be answered and a preliminary design developed. Upon completion of such a design, cost estimates may be compared with the cost of more conventional treatment.

CHAPTER II

OBJECTIVES AND SCOPE

The objective of this research is to develop a technique for designing in-channel supplemental aeration systems for the Houston Ship Channel and demonstrate this technique by developing a preliminary design for two alternative systems. The alternative designs include site location, unit sizing, intake and discharge location when applicable, and other information appropriate to a preliminary design. Systems will be designed to meet two dissolved oxygen criteria: 2 mg/l and 4 mg/l. Two mg/l is the present criterion set for the channel between the turning basin and the San Jacinto Monument by the T.W.Q.B. and approved by the E.P.A.[5] The second criterion, 4 mg/l DO, is selected because it is the T.W.Q.B. criterion below the monument and it is the proposed E.P.A.[13] lower limit on DO in estuarine waters. Supplemental aeration systems are designed to meet these criteria under the worst expected conditions for dissolved oxygen with provision made for reduction of system capacity during less severe conditions.

The geographical area of investigation is limited to the reach of the Houston Ship Channel corresponding to Texas A&M University (TAMU) river miles 10 through 24.5 as shown in Fig. 2.1. The increased discharge due to the inflow of the San Jacinto River combined with the lower reaches of the channel. As illustrated in Fig. 2.2 the DO concentration steadily increases from mile 10 to mile zero while miles 10

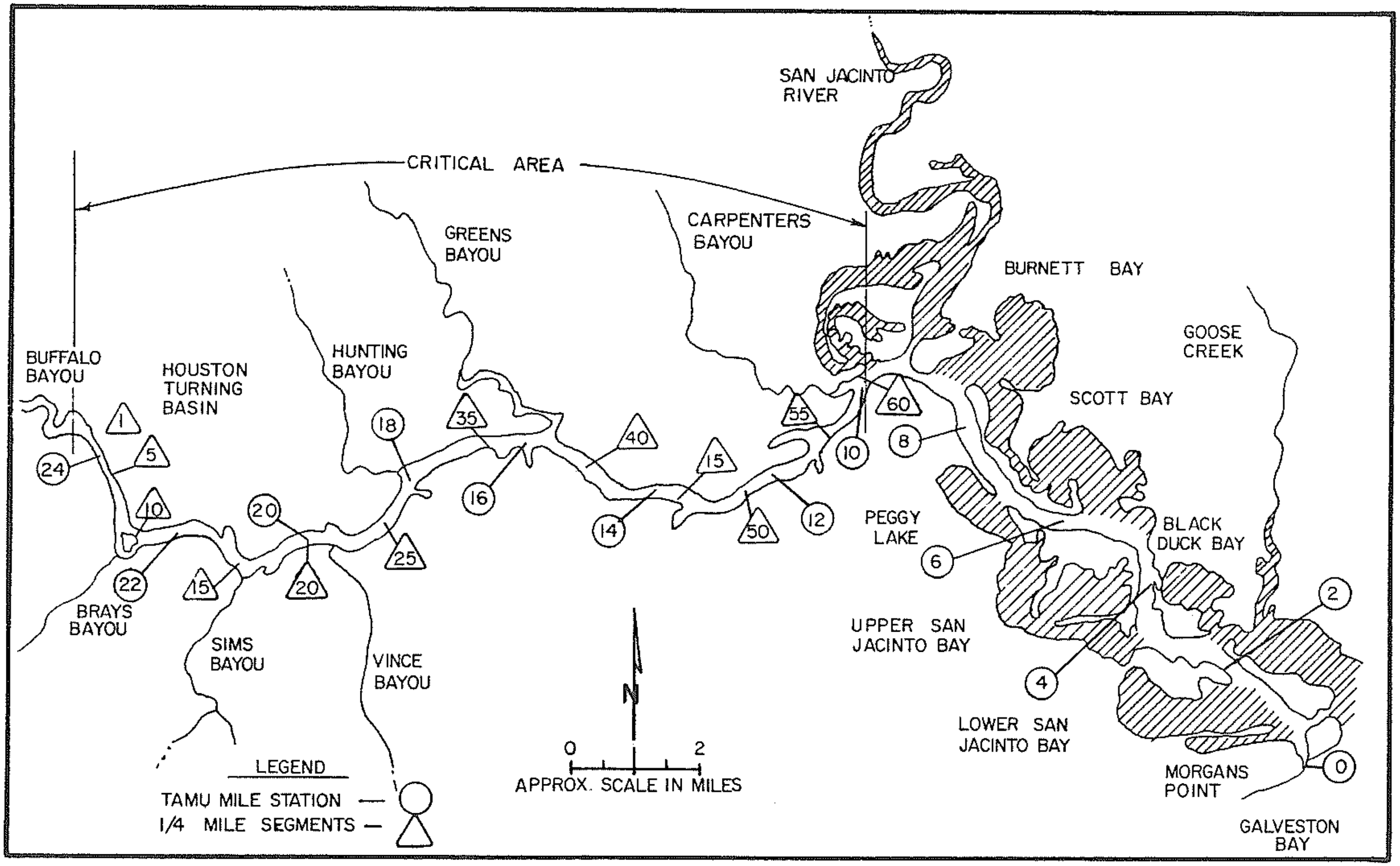

Fig. 2.1 Map of the Houston Ship Channel

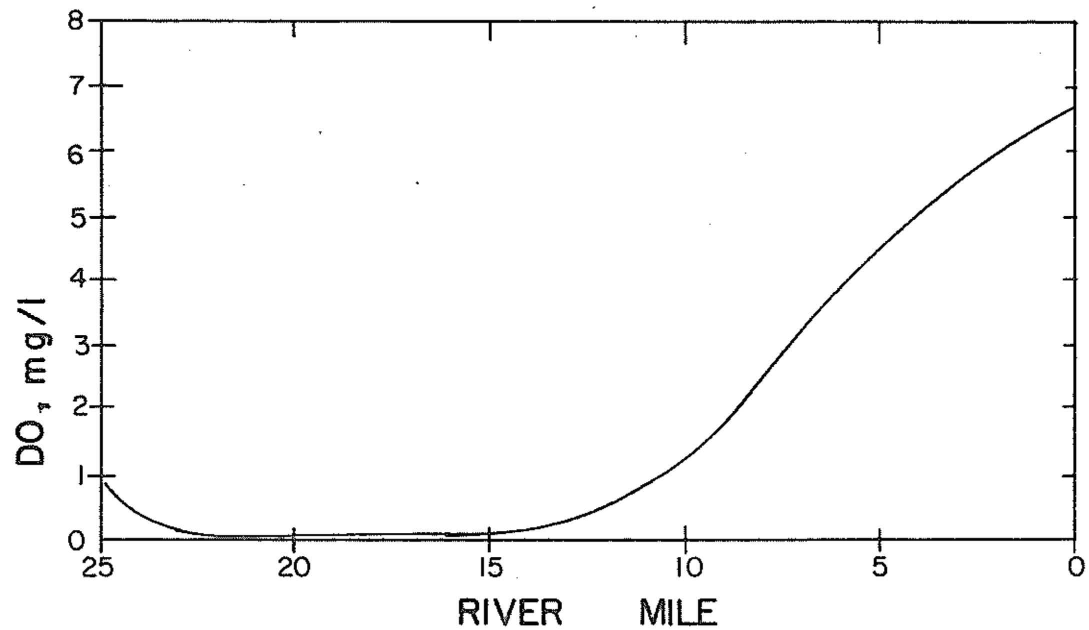

Fig. 2.2 Typical Summer Dissolved Oxygen Concentration In The Houston Ship Channel

through 24.5 often have no DO and are anaerobic. This situation has caused the Gulf Coast Waste Disposal Authority and Texas A&M Research Foundation to identify the upper 14.5 miles of the channel as the critical zone for DO concentration.[6]

Aeration devices to be studied are: 1) floating surface aerators, 2) diffused aerators, 3) sidestream pure oxygenation, 4) diffused pure oxygen. Floating surface aerators are basically electric water pumps which transfer oxygen by spray and turbulence (Fig. 2.3). Diffused aerators consist of compressed air and header pipes with air diffusers, placed under water, as illustrated in Fig. 2.4. Sidestream oxygenation systems remove a small portion of the channel flow, add molecular oxygen in order to super-saturate the water, and return the oxygenated water to the bottom of the channel where it is diffused, as shown in Fig. 2.5. Diffused pure oxygen systems are the same as diffused aerators except compressed oxygen replaces compressed air.

This research is concerned with development of the supplemental aeration data necessary to compare this alternative with advanced point source treatment. Therefore, non-point waste sources, such as urban stormwater runoff, are not considered. However, separate research is being conducted on the subject of non-point source pollution of the Houston Ship Channel and when this information becomes available the modeling portion of this study may be easily updated to include non-point pollution.

Only aeration sites located in the ship channel are considered. Hydraulic modifications or placement of aeration equipment in convergent channels is not evaluated. The analysis of water movement and system

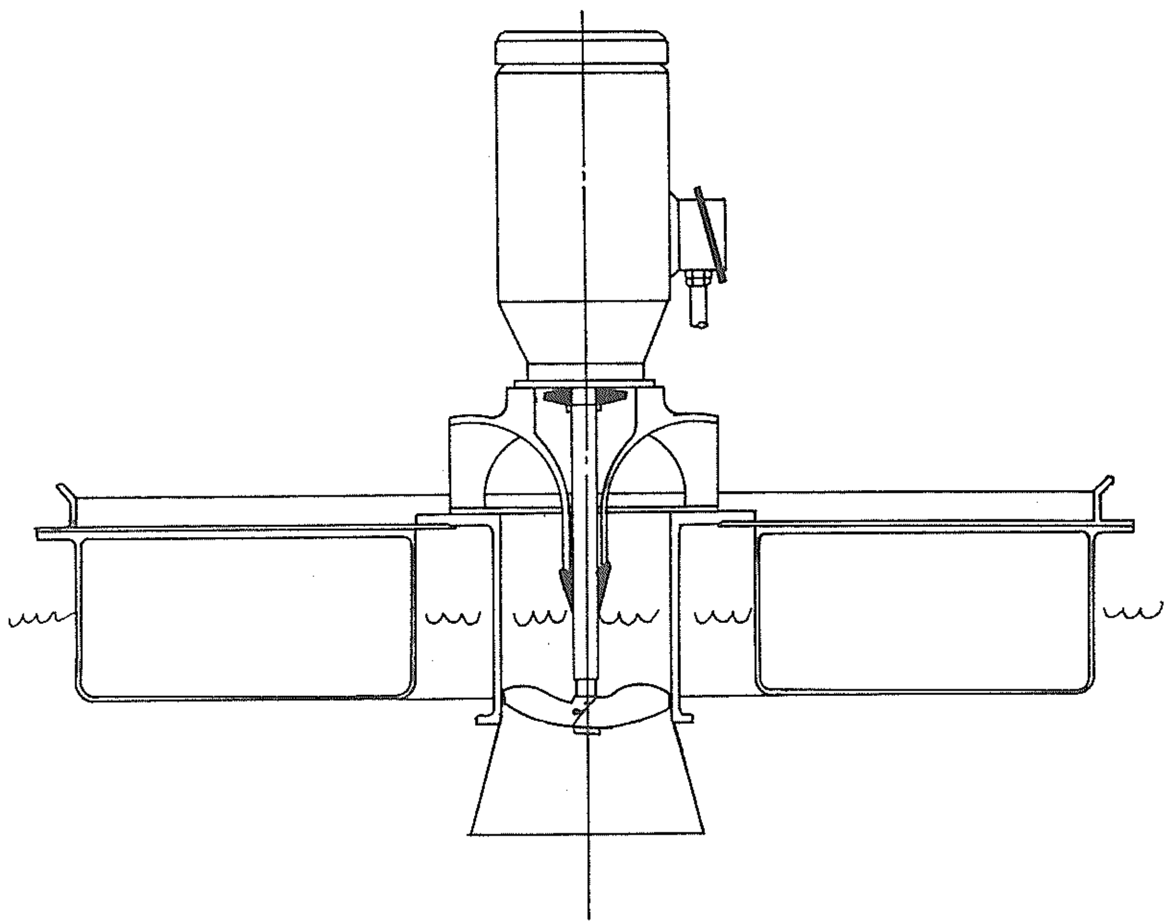

Fig. 2.3 Surface Aerator

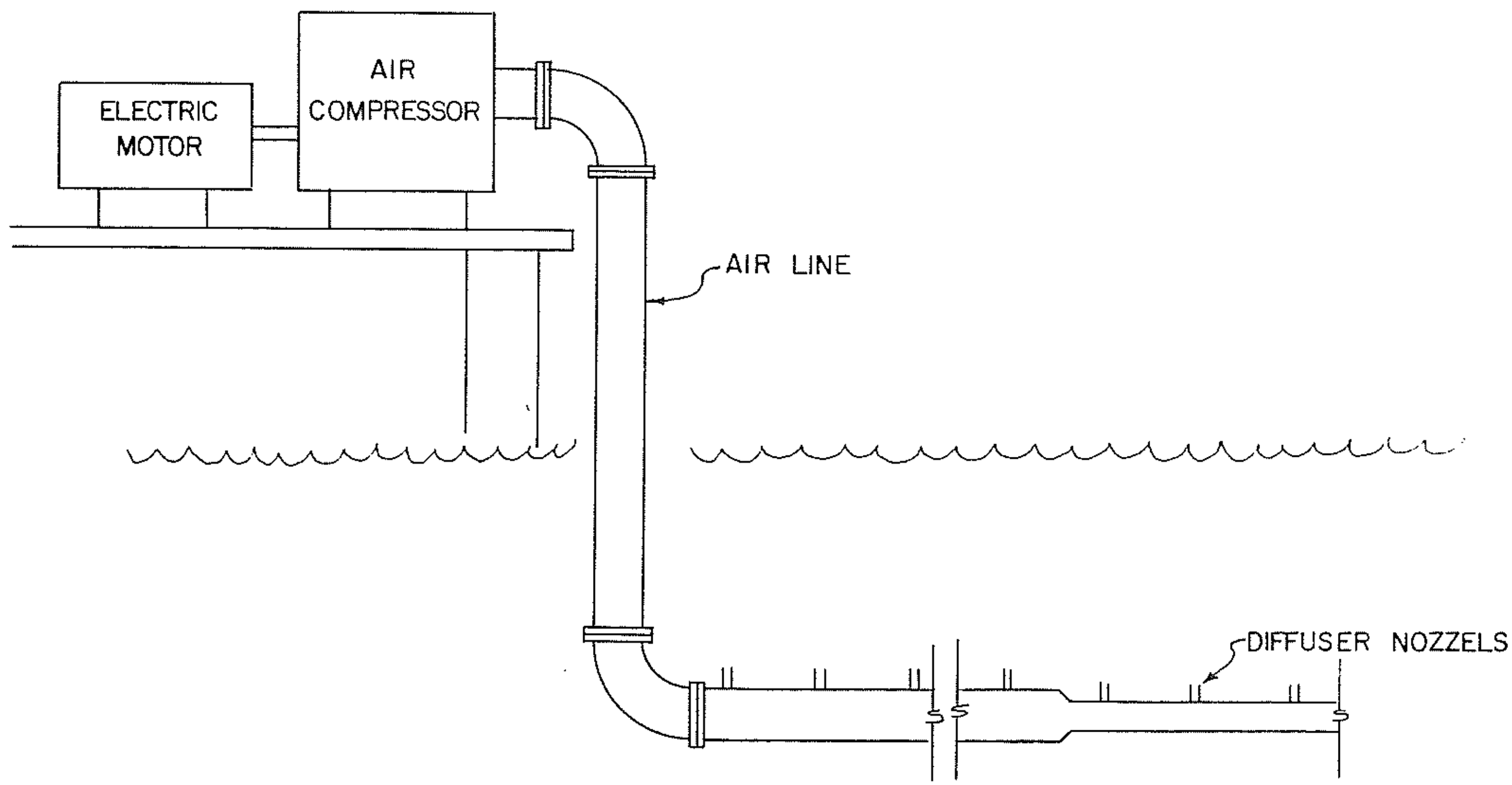

Fig. 2.4 Diffused Aerator

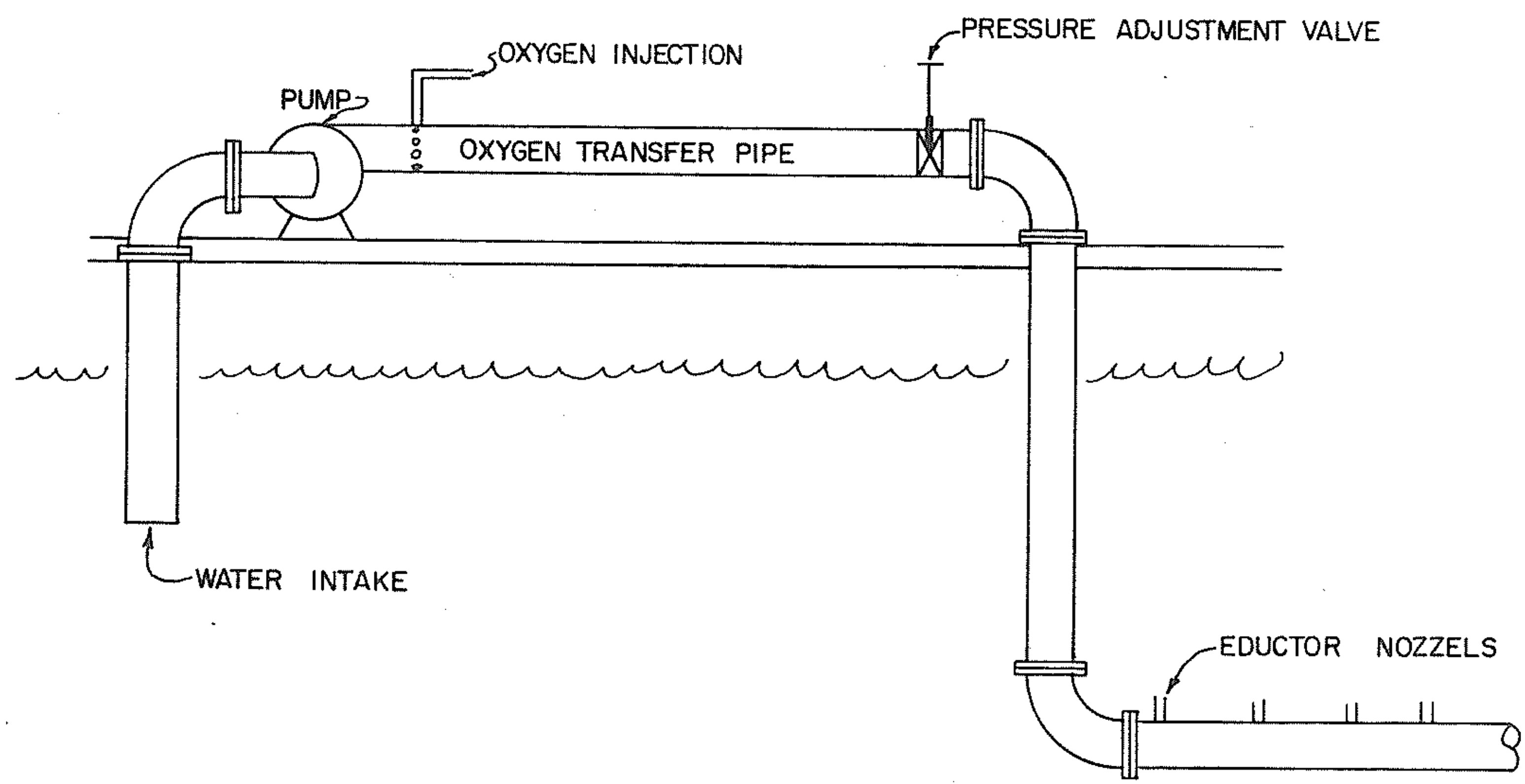

Fig. 2.5 Sidestream Oxygenation System

dynamics necessary for accurate simulation of the many possible extra channel sites is beyond the scope of this research.

CHAPTER III

LITERATURE REVIEW

Literature available on supplemental aeration has been reviewed and reported on by several researchers. In 1966 Thackston and Speece reviewed supplemental aeration of flowing streams and concluded that weirs and turbine aeration are inexpensive, whereas diffused-air and surface aeration are more costly and have limited use.[14] Conversely, in 1970 Hogan, Reed, and Starbird[15] evaluated costs of reaeration in a hypothetical stream and report surface aeration to be the most economical method.

King in 1970 reviewed and analyzed the literature on supplemental aeration.[16] He reports that the literature reflects a large amount of information on reaeration in waste treatment plants, but the application of these theories and methods to large volumes of water, such as rivers and reservoirs remains to be developed. Questions remain concerning atmospheric reaeration in streams according to King. He also reports there is an apparent deficiency in economic analysis and cost comparison of methods and devices for reaeration. King points to the many difficulties facing designers of reaeration systems and states that research activity in this field has not been collected into a set of criteria for design purposes.

JBF Scientific Corporation[17] reviewed the literature in 1971 and developed a simplified method for designing aeration systems. No computer modeling is proposed and an effort is made to reduce the sophistication of stream modeling in order to simplify aeration system design. Under these conditions the authors report surface aerators, diffusers, U-Tubes, and sidestream mixing are the preferred techniques below 5.0 mg/l DO, while above 5.0 mg/l molecular oxygen through side-stream mixing, U-Tubes, and possibly diffusers should be considered, depending on the volume of water.

William Whipple, Jr., and his colleagues at Rutgers University have done extensive research on supplemental aeration of New Jersey rivers. In 1969, Whipple, et al.[18], reported on pilot scale surface and diffused aeration systems in the Passaic River. The Passaic is a minor river with an average discharge of 400 cfs. The aeration site was an excavated basin approximately 100 feet square and 8 feet deep cut in the originally 2- to 4-foot-deep river. A 75 horsepower (HP) floating surface aerator was used for mechanical aerator testing, and a diesel-powered positive displacement blower feeding two 8-inch-diameter, 80-foot-long headers with air diffuser nozzles was used for diffuser testing. Actual performance tests indicated the surface aerator efficiency was 2.1 pounds of oxygen transferred per horsepower hour (lb. O_2/HP-hr) at 20° C and zero mg/l DO, i.e. standard conditions. Economic analysis subsequently indicated that the annual cost per HP of both systems was approximately $150 but, due to the poorer efficiency of the diffused aerator, surface units were recommended for the complete system. Whipple, et al., point out that their study is specific to the Passaic and other conclusions can be arrived at for other rivers.

Hunter and Whipple[19], 1970, reporting further on the Passaic study, reiterate their previous findings and report that the conclusions pertain to small non-tidal rivers.

Whipple, Coughlan, and Yu[20], again reporting on the Passaic work, point out that efficiencies may vary greatly with circumstances, but the work done is sufficient to indicate that supplemental aeration should be considered as an alternative to advanced waste treatment.

Whipple, et al.[8], tested surface aerators and bottom diffusers in the Delaware River near Philadelphia in 1970. The diffuser was tested at depths up to 38 feet and is reported to decrease markedly in deeper water. Performance of the 75 HP surface aerator appeared to be somewhat improved over results previously found in the Passaic River, but test results are inadequate to determine actual efficiency because testing was cut short when a storm damaged the aerator. Cost estimates and systems analysis led to the conclusion that induced oxygenation appears to constitute an economical alternative to advanced waste treatment on the Delaware River. The authors suggest the use of structurally reinforced surface aerators in some areas, and bottom diffusers where surface units would interfere with navigation. They also suggest the investigation of oxygen diffusers for large rivers.

In 1971 the Passaic study is again reported in the form of an E.P.A. project report[8], but no new information is brought out.

There have been several studies of surface aerators in small streams. Burns, St. John, and O'Conner[21] report tests of two 15 HP aerators on the Jackson River in Corrington, Virginia. Their efficiencies range between 1.55 and 3.27 lb. O_2/HP-hr with the mean standard transfer rate equal to 2.15 lb. O_2/HP-hr.

Kaplovsky, Walters, and Sosevitz[22] reporting on tests of two 75 HP diesel surface aerators in a Chicago canal forebay indicate 1.5 to 1.8 lb. O_2/HP-hr transferred. The forebay used for the test had provision for variable discharge and an increase in transfer efficiency with increased discharge is reported.

Estuarine supplemental aeration by a surface aerator has been used in the Thames River in England and the transfer efficiency of a 200 HP unit is reported to be 1.86 lb. O_2/HP-hr.[23] The aerator was installed by Thames Board Mills Ltd. and a comprehensive report has been prepared.

Bench scale tests of a surface aerator were conducted by Susag, Polta, and Schroepfer in a laboratory channel. Transfer rates ranging from 4.02 to 5.41 lb. O_2/HP-hr are reported by the authors but these values are much higher than full-scale test values and have doubtful field application.

Doyle[24] studied systems of 2, 3, and 4 surface units at one site in the Miami River near Miamisburg, Ohio. The Miami River is approximately 240 feet wide with a maximum depth of 10 feet at the test location. The author reports transfer rates ranging from 1.91 to 2.61 depending on the discharge. The average efficiency reported was 1.84 lb. O_2/HP-hr.

Reaeration of streams with molecular oxygen is a relatively new idea and only a few studies have been conducted. Amberg, Wise, and Aspitarte[25] have studied aeration with molecular oxygen by venting the oxygen into power turbines, by oxygen diffusers, and by sidestream oxygenation. Using turbines, oxygen absorption as high as 40 percent was observed. Diffused oxygen systems indicate 22 percent efficiency, while sidestream efficiency reached 55 percent at a water pressure of 68 psig.

Amberg and Wise[26], reporting further on sidestream oxygenation, indicate that diversion and super-saturation of 1.64 percent of the discharge of the Pearl River in Louisiana was sufficient to raise the river DO from 4 to 6 mg/l.

Speece[27] studied the gas transfer kinetics of oxygen reaeration systems and reports 80 percent absorption from an oxygen bubble through 40 feet of tap water.

Cooper[9] reviewed the available literature on oxygenation and applied it to the Houston Ship Channel. Without attempting a system design, he estimated the cost of sidestream oxygenation to be 1.4 cents per pound of oxygen transferred. He proposed obtaining molecular oxygen from a pipe line which presently runs approximately parallel to the channel from river mile 10 to river mile 17.

Mathematical models have been used to predict the effects of supplemental aeration on the Houston Ship Channel. Benson[28] modeled the effects of surface aeration systems made up of two and four sites with surface aerators totaling 600 HP at each site. He concluded that two 600 HP aeration sites would have little effect on DO at low flow summer conditions, but that BOD_U would be reduced. Four aerator sites are reported to increase the DO in the vicinity of the sites, but the effects diminish with distance from the site. Because Benson's primary concern was development of a model, no design or cost estimates are given. Calibration for the ship channel was not undertaken.

Consultants to the T.W.Q.B. have modeled supplemental aeration as subordinate parts of other studies. Espey[10], using an anaerobic model, i.e. a model which calculates negative DO concentrations, indicates that some change in DO occurs when 138,000 pounds per day of oxygen are introduced just upstream of the turning basin. However, no calibration of either model is given and, as a result, the increased DO concentration due to supplemental aeration cannot be quantified. No particular aerator type is used; rather the natural reaeration rate is greatly magnified to produce the desired oxygen addition. Hydroscience, Inc.[11], reporting to the T.W.Q.B., predicts that 25,000 pounds per day of oxygen transferred at mile 20 will increase the DO in the locality of the aerator (plus and minus 0.5 miles) to 2 mg/l DO after secondary treatment is adopted by all polluters. The steady state model used is only calibrated to fall within one mg/l of field data points through most of the critical zone. No specific aerator type was studied and no cost analysis was made.

Several studies have been conducted on the use of supplemental aeration in lakes and reservoirs[29,30,31,32,33], but these studies were primarily concerned with destratification and have limited application to the Houston Ship Channel.

Optimization theory has been applied to instream aeration in order to develop control policies for both strat-up and steady-state situations[34,35]. Optimization has also been applied to a system of equidistant aerators under dynamic conditions.[36] These studies are theoretical in nature and are unproven in complex design situations.

In summary, a review of the literature at this time reveals that many of the information gaps reported by King in 1970 still exist. Economic analysis and cost comparison of the available systems have been limited to two or three equipment types in small rivers. Research data has not been developed into a set of criteria for use in system design. Modeling of supplemental aeration in the ship channel has been undertaken, but these studies are either done with uncalibrated models or do not model any particular aerator type. Modeling efforts have not led to a supplemental aeration system design.

CHAPTER IV

MATHEMATICAL MODEL

Mathematic modeling of physical and chemical phenomena in order to predict water quality is a flexible tool in environmental engineering. Model sophistication is widely varied and model selection must be made on the basis of required accuracy. A supplemental aeration system design for large bodies of water requires accurate prediction of DO. An error of 1.0 mg/l DO in the channel is approximately equal to 10,000 pounds of oxygen per mile or 155,000 pounds for the upper channel. At 5 cents per pound of supplemental oxygen transferred and a mean downstream velocity of 0.5 fps the cost differential due to an error of 1.0 mg/l in predicted DO is equal to 62,000 dollars per day. To minimize modeling error, emphasis is placed on selection of the basic model, accuracy of oxygen dynamics simulation, and model verification.

Model Selection

Benson[28] developed a dynamic model specifically for supplemental aeration which has several advantages. The mass balance equation given by Benson is:

$$\frac{1}{A}\frac{\partial}{\partial t}(AC) + \frac{1}{A}\frac{\partial}{\partial X}(AUC) = \frac{1}{A}\frac{\partial}{\partial X}\left(AE_L\frac{\partial}{\partial X}\right) + \frac{r_i}{\rho} + \frac{r_e}{\rho} \qquad (4.1)$$

where:
- A = cross-sectional area
- C = concentration
- V = tidal velocity
- E = longitudinal dispersion coefficient
- ρ = fluid density

r_i = time rate of decay of a substance per unit volume
r_e = time rate of increase of a substance per unit volume
X = longitudinal distance measured along the axis of the estuary
t = time measured in any consistent units

The implicit formulation of finite-difference approximation of equation (4.1) is used in the model. This formulation requires more calculation time than the explicit method; however, stability requirements are not as strict allowing more flexibility in setting time and distance increments. Also, accuracy with the implicit method is greater over a wider range of conditions. The achieved accuracy combined with dynamic system simulation allows calculation of system response time. Benson reports large response times when modeling surface aeration in the ship channel, indicating that steady state models are inadequate in this respect.

The model is flexible and lends itself to changes in programming. In order to more accurately describe the kinetics of oxygen utilization and replenishment the oxygen dynamics of the model are extensively modified. Modifications providing for the calculation of segmented oxygen requirements necessary to meet criteria have also been made. All modifications to the basic model are described in following sections.

Dissolved Oxygen Dynamics

In order to more accurately simulate the oxygen dynamics of the channel several modifications of the basic model are made and described herein. The following sources and sinks of oxygen are used and will be defined mathematically in this chapter:

Sinks	1.)	Carbonaceous Decay
	2.)	Nitrification
	3.)	Benthic Demand
Sources	1.)	Natural Reaeration
	2.)	Photosynthesis
	3.)	Supplemental Aeration

The oxygen sinks are affected by the processes of waste sedimentation and carbonaceous putrefaction.

Carbonaceous Decay. The primary oxygen sink in the ship channel is the decay of organic matter. The rate of change of oxygen concentration due to carbonaceous decay is given by:

$$\frac{dC}{dt} = K_d C \tag{4.2}$$

where

C = ultimate BOD, BOD_U
t = time
K_d = Carbonaceous decay constant

Reynolds and Eckenfelder[37] determined K_d values for composite channel samples taken in February, March, and April of 1969 and their results are presented in Table 4.1. More recent research in this area is not available; therefore, these values are assumed to be representative of current conditions.

The BOD_U of the channel is sometimes assumed to be 1.5 times the BOD_5.[28,11] To check this assumption the weighted average of the K_d values presented in Table 4.1 is taken and found to be 0.234 day^{-1}. The following equation is used to calculate the ratio of BOD_5 to BOD_U[38]:

$$\frac{BOD_5}{BOD_U} = 1-e^{-0.234\,(5)} \tag{4.3}$$

TABLE 4.1

Carbonaceous Decay Coefficients

River Mile	K_d* (day^{-1})
24	0.15
20	0.27
16	0.31
12	0.24
10	0.29

*Base e, 20° C

$$\frac{BOD_5}{BOD_U} = 0.69$$

$$BOD_U = 1.449\ BOD_5$$

This calculation confirms the 1.5 value used in previous research.

The temperature correction for K_d as given by King[16] for temperatures in the range 15-32°C is:

$$K_{d(t)} = K_{d(20)} \quad (1.047^{T-20}) \tag{4.4}$$

where T = °C.

Nitrification. Nitrification, unlike the heterotrophic oxidation of organic matter, is carried out by only a few autotrophic microbes under very specific conditions. The reaction proceeds in two steps, the first being carried out by bacteria of the genus *Nitrosomonas* as follows:

$$NH_4^+ + \frac{3}{2}\ O_2 \rightarrow\ NO_2^- + 2H^+ + H_2O \tag{4.5}$$

The second step, nitrite oxidized to nitrate, is accomplished by bacteria of the genus *Nitrobacter*, as follows:

$$NH_4^+ \ + \ 2O_2 \rightarrow NO_3^- \ + \ 3H^+ \ + \ H_2O \tag{4.6}$$

Equations (4.5) and (4.6) represent the oxidation of ammonia or nitrite for energy, excluding oxidation for synthesis. Both genera of nitrifers synthesize cell mass from ammonia, inorganic carbon, and essential minerals. The equation for synthesis as presented by McCarty[39] is:

$$4CO_2 + HCO_3^- + NH_4^- + H_2O \rightarrow C_5H_7NO_2 + 5O_2 \tag{4.7}$$

On the basis of laboratory studies and theoretical calculations, McCarty gives the following overall reaction for the biological oxidation of ammonia to nitrate:

$$22NH_4^- + 37O_2 + 4CO_2 + HCO_3^- \rightarrow C_5H_7NO_2 + 21NO_3^- + 20H_2O + 42H^+ \qquad (4.8)$$

Stoichiometrically equation (4.8) indicates that 3.63 parts of oxygen are reduced in the autrophic oxidation of one part of $NH_3 - N$.

The first order decay equation for nitrification, in differential form is:

$$\frac{dN}{dt} = K_n N \qquad (4.9)$$

where

N = nitrogenous BOD
t = time
K_n = ammonia decay coefficient in base e, time^{-1}

Reynolds and Eckenfelder[37] determined K_n for samples of ship channel water taken in June 1969. Their results are summarized in Table 4.2. The average of the reported values is 0.31/day which compares favorably to 0.37/day found by Whipple.[18]

Nitrifying bacteria are much more sensitive to environmental conditions such as temperature and DO than are heterotrophs. O'Conner[40] gives the effects of temperature on the rate kinetics of nitrification as:

$$K_{n(t)} = K_{n(20)}\ 1.09^{(T-20)} \qquad (4.10)$$

where $T = {}^oC$.

TABLE 4.2

Nitrogen Decay Coefficients

Miles Above Morgan's Point	K_n* (day^{-1})
24	0.44
22	0.43
20	0.38
18	0.33
16	0.25
15	0.25
12	0.25
11	0.25
10	0.25
9	0.25

The effects of DO on the kinetics of nitrification are significant. Unlike carbonaceous decay which is described by first order kinetics down to approximately 0.2 mg/l, the rate of oxidation of ammonia varies throughout the range of DO concentration. Hydroscience, Inc.[11] compiled data taken from the literature and fitted a curve to it (Fig. 4.1). In their modeling effort, however, Hydroscience, Inc. only required the accuracy provided by the following relationships:

$$\begin{aligned} &DO < 1.5 \text{ mg/l}, \; K_n = 0.0 \\ &DO > 1.5 \text{ mg/l}, \; K_n = \text{maximum} \end{aligned} \qquad (4.11)$$

The current work is primarily concerned with DO concentrations in the range zero to 4 mg/l where nitrification can vary from nonexistent to 80 percent of the maximum. In reaches where the nitrogenous oxygen demand is double the carbonaceous demand, the error created by assuming the same K_n at 2 mg/l DO to be equal to K_n at 1 mg/l DO would result in a 20 percent error in calculated oxygen demand, and a proportionate error in the required capacity of supplemental aeration equipment.

To obtain the accuracy required in this research the Hydroscience, Inc. curve was approximated by the following modified Michaelis-Menton equation:

$$K_{n(DO)} = \frac{(1.143\, \hat{K}_n)\,(DO)}{1.4 + DO} \qquad (4.12)$$

where

$\hat{K}_n$ = Maximum K_n, i.e., K_n at 9 mg/l DO

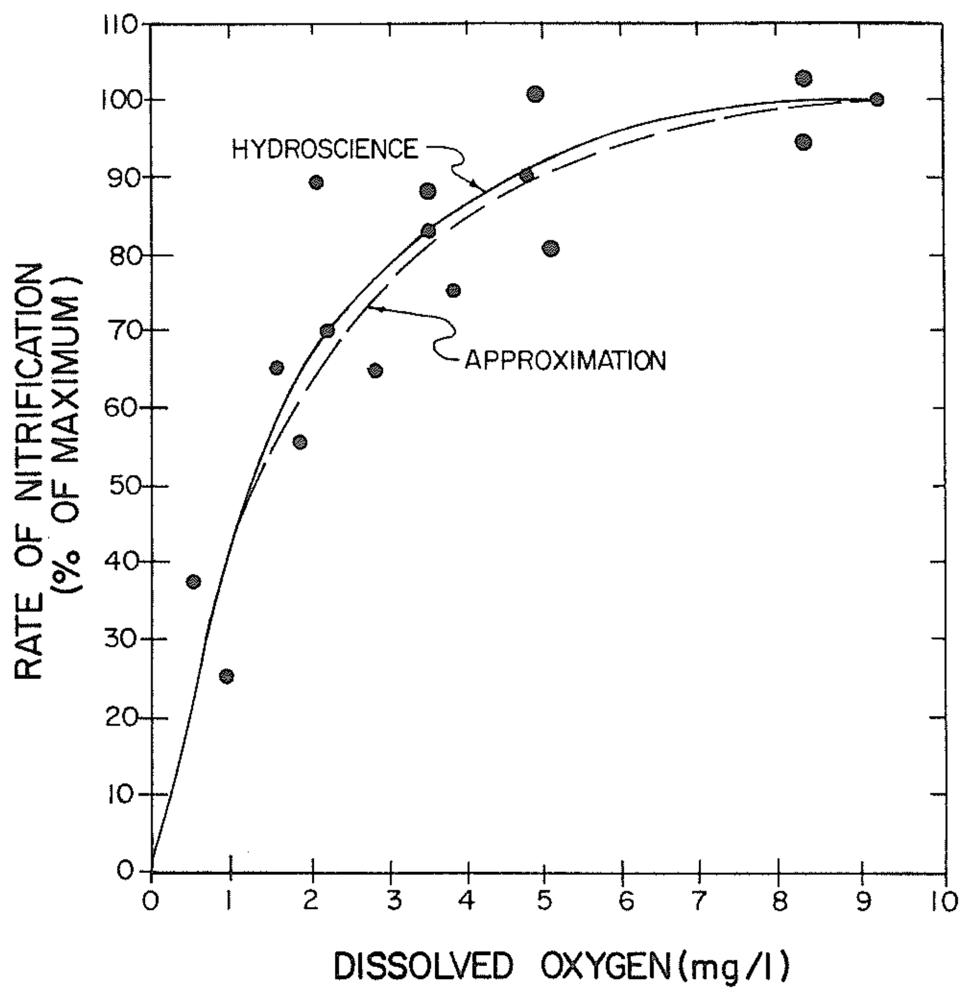

Fig. 4.1 Nitrification Rate vs. Dissolved Oxygen

$K_{n(DO)}$ = fraction of K_n at a particular DO

DO = mg/1

As shown in Fig. 4.1 (p. 27) equation (4.12) (p.26) very closely approximates the original curve.

The Reynolds and Eckenfelder decay rates presented in Table 4.2 (p. 25) are corrected to 9 mg/1 DO in order to use equation (4.12) (p. 26). They use the Marais technique[41] and let the DO drop about 1.5 mg/1 before resaturating the sample. This indicates that the average DO during the tests was approximately 7.7 mg/1. Using this DO concentration, $\hat{K}_n$ for the various reaches is calculated and fed into the model. Equation (4.12) (p. 26) is then used by the model to calculate K_n at varying DO concentrations.

<u>Benthic Demand</u>. The accumulated benthic sludges are a major oxygen sink in the channel. Reynolds, et al.[42] have studied the benthic demands using electrolytic BOD apparatus and their results are reported in Table 4.3.

The benthic oxygen demand rate, B_r, is corrected for temperature as described by Reynolds:

$$B_{r(T)} = B_{r(32)} \quad (1.055^{T-32}) \tag{4.13}$$

where $T = {}^{o}C$.

<u>Natural Reaeration</u>. Eckenfelder and O'Conner[43] give a good description of the kinetic equations representing oxygen transfer into water at the interface:

$$\frac{dm}{dt} = D_g A \left(\frac{dc}{dy}\right)_1 = D_L A \left(\frac{dc}{dy}\right)_2 = D_e A \left(\frac{dc}{dy}\right)_3 \tag{4.14}$$

TABLE 4.3

Benthic Oxygen Demand

River Mile	Benthic Oxygen Demand Rate $gm/hr\text{-}m^2$ at 32° C
24	0.16
22	0.20
20	0.22
18	0.19
16	0.15
14	0.13
12	0.125
10	0.12

where

$\frac{dm}{dt}$ = rate of mass transfer

A = area

D_g = molecular diffusivity of the gas through the gas film

$\left(\frac{dc}{dy}\right)_1$ = concentration gradient through the gas film

D_L = molecular diffusivity of the gas through the liquid film

$\left(\frac{dc}{dy}\right)_2$ = concentration gradient through the liquid film

D_e = eddy diffusivity of the gas in the liquid body

$\left(\frac{dc}{dy}\right)_3$ = concentration gradient in the body of liquid

The rate of mass transfer of oxygen through the liquid film is much slower than through the gas film or liquid body. Therefore, the passage of oxygen through the liquid film is the limiting step and equation (4.14) can be reduced to:

$$\frac{dm}{dt} = D_L A \frac{(C_S - C)}{y_L} \tag{4.15}$$

where

C_s = the oxygen concentration on the atmosphere side of the liquid film, i.e. saturation

C = the concentration in the liquid body

y_L = the thickness of the liquid film

Equation (4.15) is expressed in concentration units by dividing each side by the volume of the liquid:

$$\frac{dC}{dt} = \frac{D_L}{y_L} \frac{A}{V} (C_S - C) \tag{4.16}$$

Due to difficulty in determining y_L and in relating A and V accurately, equation (4.16) is often given as:

$$\frac{dc}{dt} = K_a \ (C_s - C) \tag{4.17}$$

where

K_a = the reaeration rate coefficient ($time^{-1}$)

$C_s - C$ = oxygen deficit or "driving force"

It can be seen from equation (4.17) that the reaeration rate coefficient and the oxygen deficit are of primary concern in modelling atmospheric reoxygenation. Oxygen deficit is dependent on the oxygen saturation value, C_s, under field conditions. The value of C_s is influenced by the partial pressure of oxygen in the atmosphere, water temperature, and salinity. Corrections must be made to account for these influences.

Henry's law gives the relationship between C_s and the partial pressure of oxygen in the atmosphere as:

$$C_s = Hs\ p \tag{4.18}$$

where

p = partial pressure of O_2
Hs = Henry's law constant, 43.8 mg/l-atm. for O_2 in water at $20^{\circ}C$

The fraction of oxygen in air varies only slightly from 21 percent and atmospheric pressure varies within the range 0.996 to 1.004 atmospheres at sea level. Applying Henry's law, the expected variation of C_s due to changes in partial oxygen pressure is 9.235 mg/l to 9.154 mg/l. This variation is insignificant and no correction is made for it.

Water temperature and C_s are inversely proportional and Thowmann[44] gives the following empirical equation for the relationship:

$$C_s = 14.65 - 0.41022T + 0.0079910T^2 - 0.000077774T^3 \qquad (4.19)$$

where T = ^oC.

Equation (4.19) approximates C_s very closely as demonstrated in Table 4.4.

The salinity significantly reduces C_s in estuaries and the correction used by Hann[45] is:

$$C_{s(Sal)} = C_s - (Sal.)\ 0.0841 - 0.00256\ (T) + 0.00374\ (T)^2 \qquad (4.20)$$

where

$C_{s(Sal.)}$ = C_s corrected for salinity

T = ^oC

Sal. = salinity (ppt)

The equation used for calculating C_s in this research is a combination of equations (4.19) and (4.20):

$$C_s = (14.62)\ (2.71828 - 0.0389436T\ 0.82626) - (Sal.)\ 0.0841 - 0.00246\ (T) + 0.000374\ (T)^2 \qquad (4.21)$$

Considerable research has gone into determining the value of the reaeration rate coefficient K_a for different conditions. Attention has been given to the effects of hydraulic, physical, and meteorological characteristics. A number of researchers have evolved formulae giving K_a as a function of depth and velocity. The best known and most used of these equations is the O'Connor and Dobbins[46] equation:

$$K_a = 12.91\ \frac{V^{0.5}}{H^{1.5}} \qquad (4.22)$$

where

V = velocity, feet per day

TABLE 4.4

Comparison of Calculated C_s Values

Temperature, C	0	10	20	30
ASCE[14]	16.65	11.27	9.02	7.44
Equation (4.19)	14.65	11.27	9.02	7.44

H = distance
K_a = reaeration rate coefficient, day^{-1}

The O'Connor and Dobbins equation has been applied to the Houston Ship Channel, but the experience of several modelers indicates that it predicts low values. Using both dynamic and steady state models, researchers have found it necessary to arbitrarily increase the predicted K_a[47], set lower limits on the predicted values of K_a[28], or select a constant K_a larger than the values predicted by the O'Connor and Dobbins equation.[48] Hydroscience, Inc.[11] is able to calibrate using the basic O'Connor and Dobbins equation, but they estimate the nitrogenous BOD load 20 to 45 percent lower than actual values. Preliminary verification runs indicate the basic O'Connor and Dobbins equation would predict low K_a values in this research as well.

In-situ measurements of K_a in the ship channel also indicate that higher reaeration rates exist than are predicted by the O'Connor and Dobbins equation. Hann et al.[49] using radioactive tracer techniques report an instantaneous $K_a = 4.46\ day^{-1}$. This value is questionably high, but it generally indicates that the maximum value of 0.07 day^{-1} [1] predicted by the O'Connor and Dobbins equation is low. Researchers suggest that the discrepancy between predicted and measured values of K_a can be attributed to wind action, ship traffic, tidal activity, or some combination thereof.

The experience of modelers and the measurement of high in-situ K_a values suggests the use of an equation that predicts higher reaeration rate coefficients than the O'Connor and Dobbins equation;

however, there are none available that are applicable. Kramer[1] reviewed reaeration rate equations and found that the O'Connor and Dobbins equation predicts higher K_a values for the ship channel than any other equation applicable to deep channels. The only equations predicting higher K_a values were derived for shallow, fast-flowing streams and are not applicable to the Houston Ship Channel.

The problem with applying the basic O'Connor and Dobbins equation to the ship channel is its dependence on velocity. At normal and low flow conditions the primary velocity in the channel is tidal, and due to the damping effect of the 40 miles of bays, channels, and inlets between the channel and the Gulf of Mexico the average tidal velocity is only 0.4 to 0.6[11] with 2, 3, or 4 slack tides per day.[50] Under these conditions the O'Connor and Dobbins equation predicts a maximum K_a of 0.06 day^{-1}, and at slack tide K_a goes to zero, a physical impossibility in unsaturated water.

An alternative to the basic O'Connor and Dobbins equation is an equation composed of a minimum coefficient representing reaeration during slack tide and the basic equation to predict increases in the coefficient during higher velocity periods. Referring to equation (4.16), the term:

$$\frac{D_L}{y_L}\left(\frac{A}{\overline{V}}\right)$$

is set equal to

$$\frac{K_L}{H}$$

where

$$H = \text{depth}$$

$$K_L = \frac{D_L}{y_L} = \text{liquid coefficient, ft/day}$$

If K_L is set to the minimum that might be expected in the channel the term K_L/H will be equal to K_a (see equation 4.17) at slack tide and low flow. K_L in the Thames Estuary is reported to vary between 4 ft./day under "calm" conditions, to approximately 20 ft./day when waves 20 inches high were observed.[51] Due to the nature of the ship channel, K_L is taken to be equal to 4 ft./day.

The phenomena which produce the minimum reaeration, i.e. shipping, wind effects, and other intangibles, do not cease to exist during higher velocity periods. Therefore, the total K_a is taken to be the sum of the K_a during minimum reaeration, K_L/H, and the K_a is produced by velocity, represented by the O'Connor and Dobbins equation. The equation thus derived is:

$$K_a = \frac{K_L}{H} + 12.91 \frac{V^{0.5}}{H^{1.5}} \qquad (4.23)$$

where

$$K_L = 4 \text{ ft./day}$$

Fig. 4.2 illustrates the K_a values predicted by equation (4.23) compared to values predicted by the basic O'Connor and Dobbins equation and compared to the Negulescu and Rajanski[52] equation derived for shallow rivers.

<u>Photosynthesis</u>. In less polluted waterways photosynthesis can add a significant amount of oxygen to the water. However, the

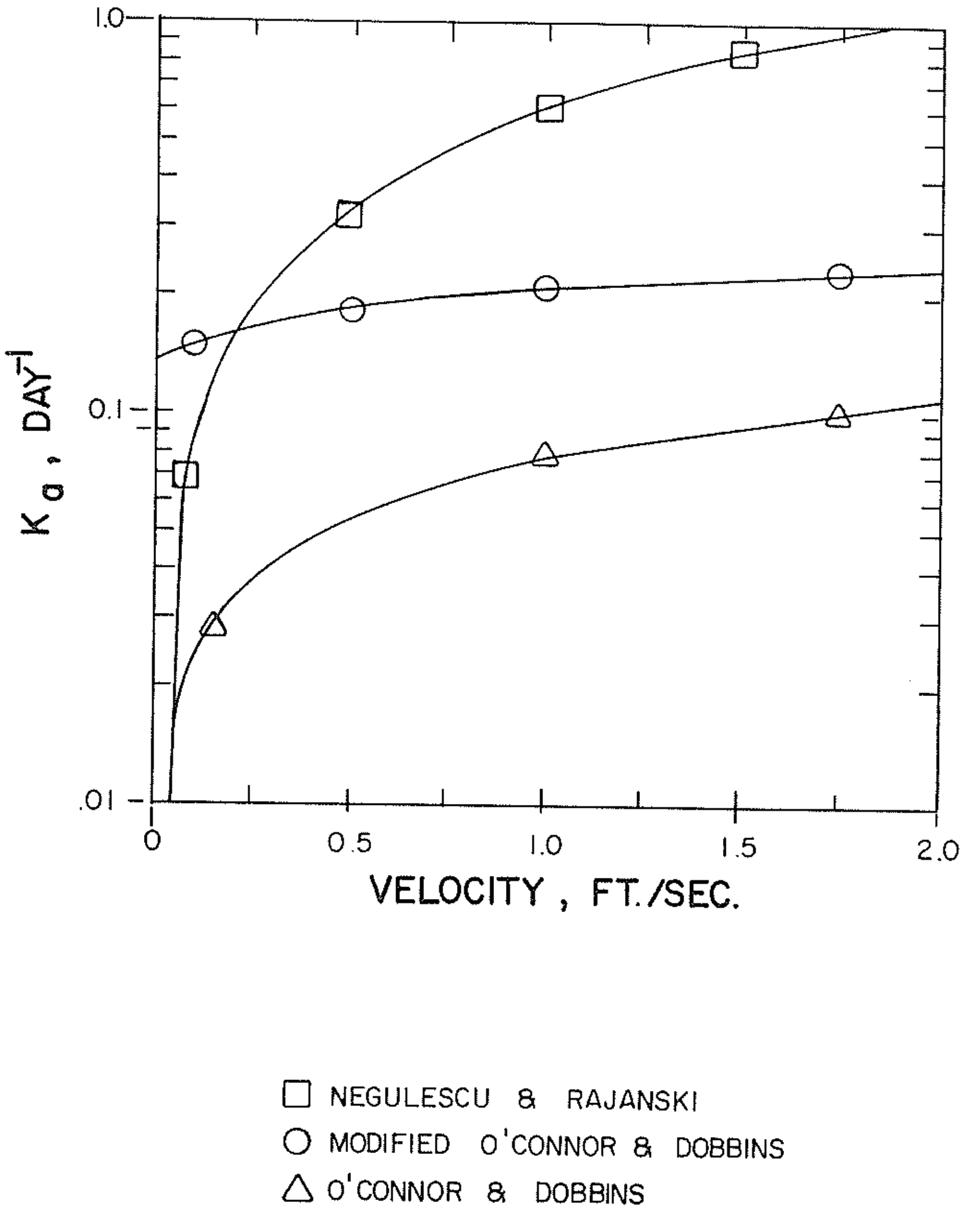

Fig. 4.2 Comparison of Reaeration Rate Equations

ship channel is so polluted with toxic organic compounds, heavy metals, and oxygen-demanding pollutants, that photosynthesis is usually ignored by modelers.[11,48,10] This assumption is substantiated by the findings of Parmer, Hopkins, and Hann[53] who report that toxic substances act in concert with limiting oxygen conditions to cause death of aquatic organisms in the channel. The authors also observed chronic toxicity of channel water. A beneficial algal population may develop after the implementation of reaeration, but that prediction cannot be confirmed at this time. For the purposes of this study photosynthesis will be ignored.

Sedimentation. Hutton, et al.[54] have studied sedimentation of wastes in the ship channel and they report 24.5 percent sedimentation of all wastes in the upper 12 miles of the channel and 32.0 percent on the average over the entire 24 miles. Sparr and Hann[55] modeled nitrogenous sedimentation and confirmed Hutton's 32.0 percent figure for overall sedimentation. Hydroscience, Inc.[11] uses 25 percent sedimentation.

In this research, sedimentation of both ammonia and carbonaceous wastes is taken to be 24.5 percent. Correction for sedimentation is made by subtracting 24.5 percent of the oxygen demand of both nitrogenous and carbonaceous wastes.

Carbonaceous Putrefaction. Carbonaceous wastes putrefy under anaerobic conditions, thereby reducing the carbonaceous oxygen demand exerted when aerobic conditions are achieved. Espey, et al.[10], emphasize the need to model anaerobic conditions and they estimate the anaerobic decay coefficient, K_x, to be 0.15 times the aerobic decay coefficient, K_d. Young and Hann[48] use $K_x = 0.08\ day^{-1}$, or approximately 0.3 K_d. For purposes of this study the more conservative value, 0.15 K_d, will be used.

Model Verification

The dissolved oxygen dynamics described above are programmed into Benson's model and presented in Appendix A . The need for accurate prediction of DO concentration in supplemental aeration design prompts a thorough verification of the model. It is considered necessary for accurate design development to predict DO concentration within 1.0 mg/l of observed field data over the ranges of DO expected after implementation of supplemental aeration. Also, it is necessary to demonstrate the ability to predict changes in the oxygen balance under dynamic conditions. The equations used to model BOD and ammonia decay must be proven by accurate prediction of BOD and ammonia concentration.

There are several conditions which make a period of time suitable for model verification. There must be oxygen present for verification of oxygen dynamics equations and a winter period offers the best opportunity to observe positive DO values. It is preferable to conduct at least one verification run for a long steady-state flow period. Also, field data must be available for the verification period.

The period from December 20, 1971 to February 10, 1972 satisfies the conditions for verification. A hydrograph for the period is compiled from Geological Survey data[56] and is given in Fig. 4.3. A relatively steady discharge of approximately 600 CFS occurred from December 20, 1971 to January 15, 1972. Four sampling dates are recorded by TAMU[57] for this period with DO values available for all four dates and BOD5 data available for one date, but ammonia data was not recorded. Concentrations of BOD5 in the waste discharges are taken from T.W.Q.B. self-reporting system data. Values of NH_3-N are assumed to be equal to those reported by the T.W.Q.B. Galveston Bay Project[58] (see Appendix B). The predicted DO and BOD_5 concentrations are compared to field data in Figs. 4.4 and 4.5 as shown. The computed DO values vary no more than 0.1 mg/l from the average of field data at any point and they are within the range of recorded field data throughout the channel. Values of BOD5 are expected to vary more than DO values due to the inhibition present in the channel[37]; however, the predicted BOD values are within 1 mg/l of the average field values and within 0.5 mg/l of the range of field values.

The increased discharge of January 31 and February 1, 1972 substantially raised the channel DO and offered an opportunity DO for 1.5 tidal cycles after the initial increase in discharge was, as shown in Fig. 4.6, within 1.5 mg/l of average field data at the most deviant point,and was within the range of values at all but one sampling station.

Immediately after the high discharge period, the system returned to a relatively steady state condition (February 3 through February 10, 1972) with an average discharge of 500 CFS. Due to higher flow and

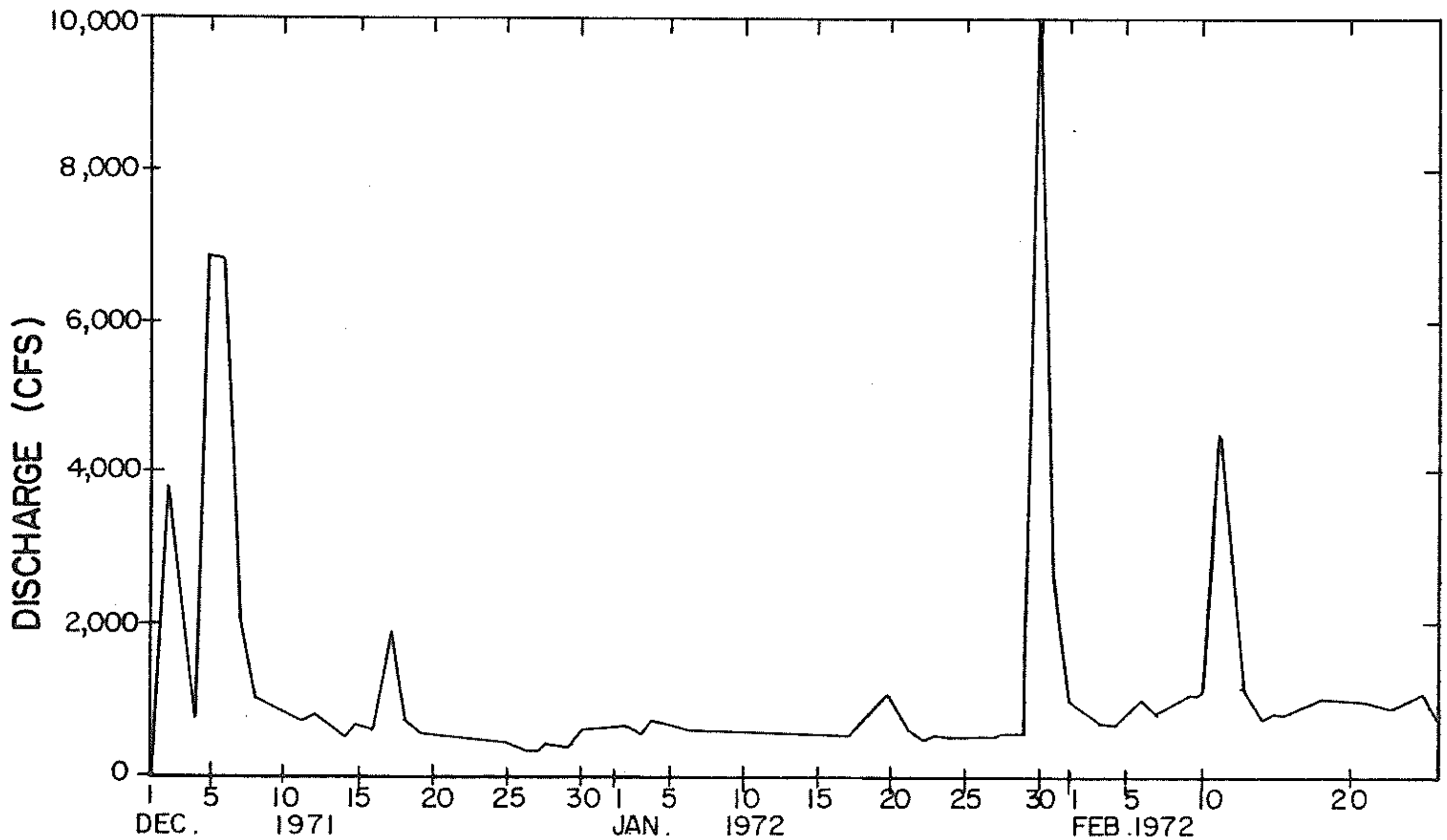

Fig. 4.3 Ship Channel Hydrograph

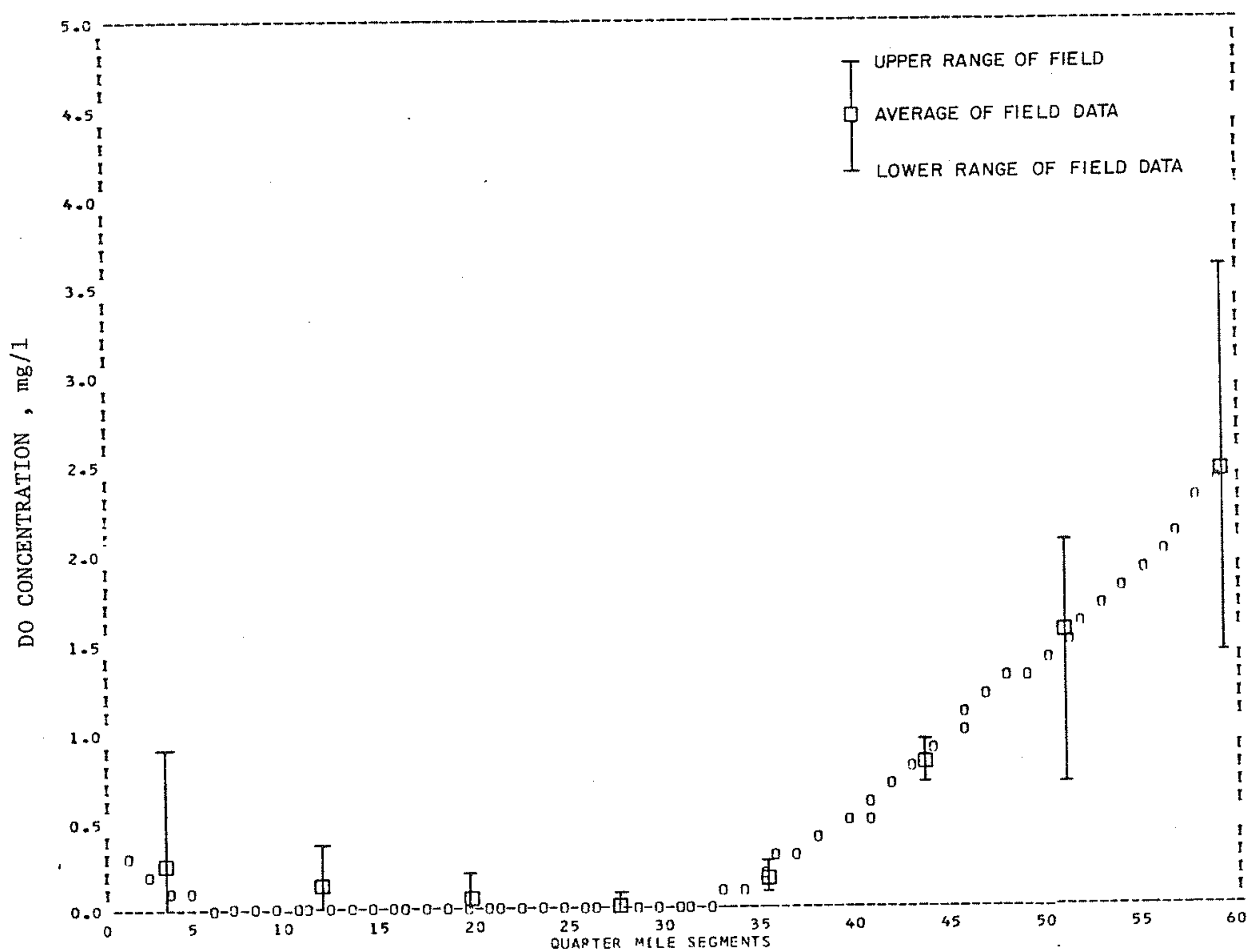

Fig. 4.4 1st Low Flow Dissolved Oxygen Calibration

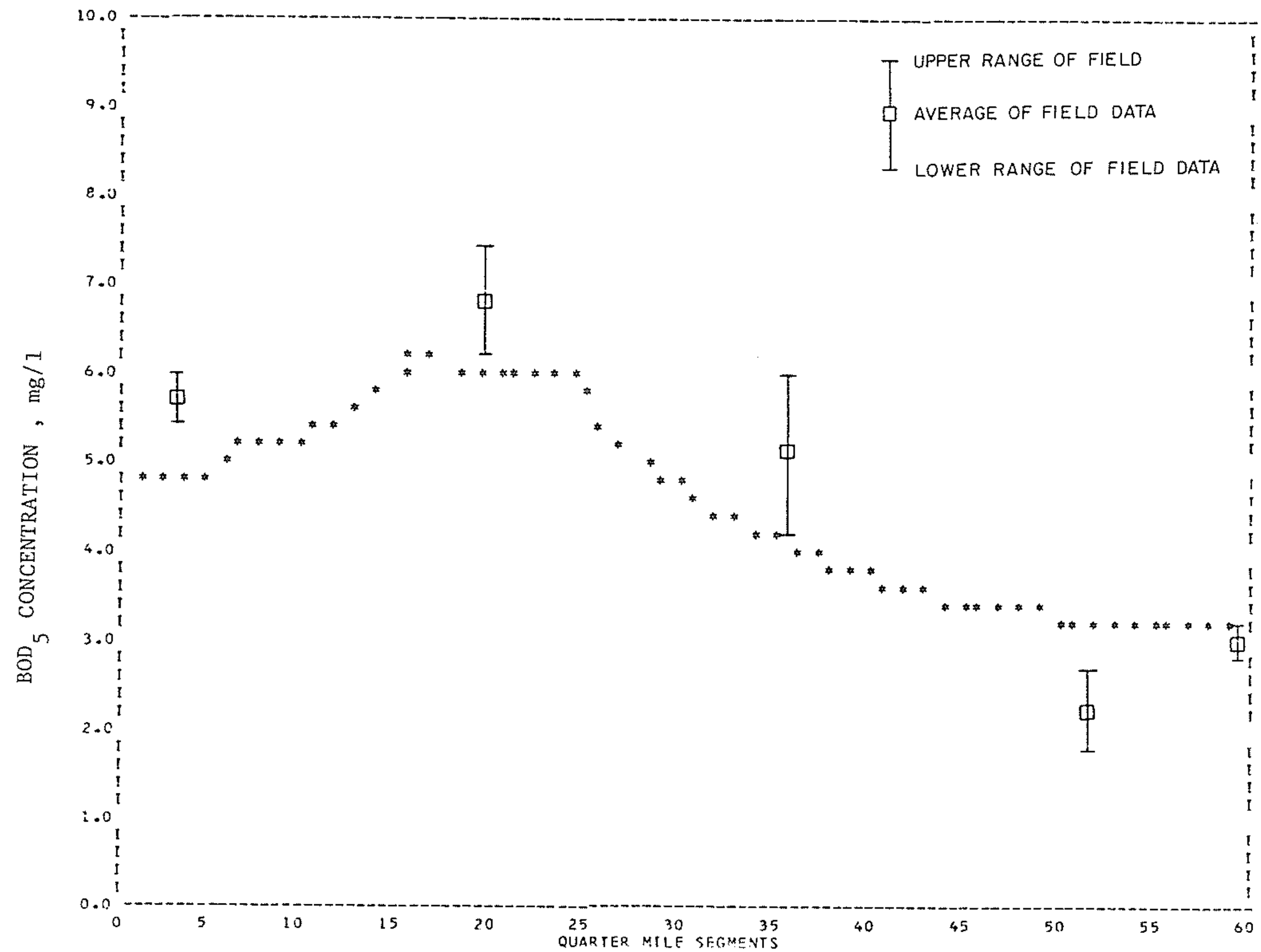

Fig. 4.5 Low Flow BOD_5 Calibration

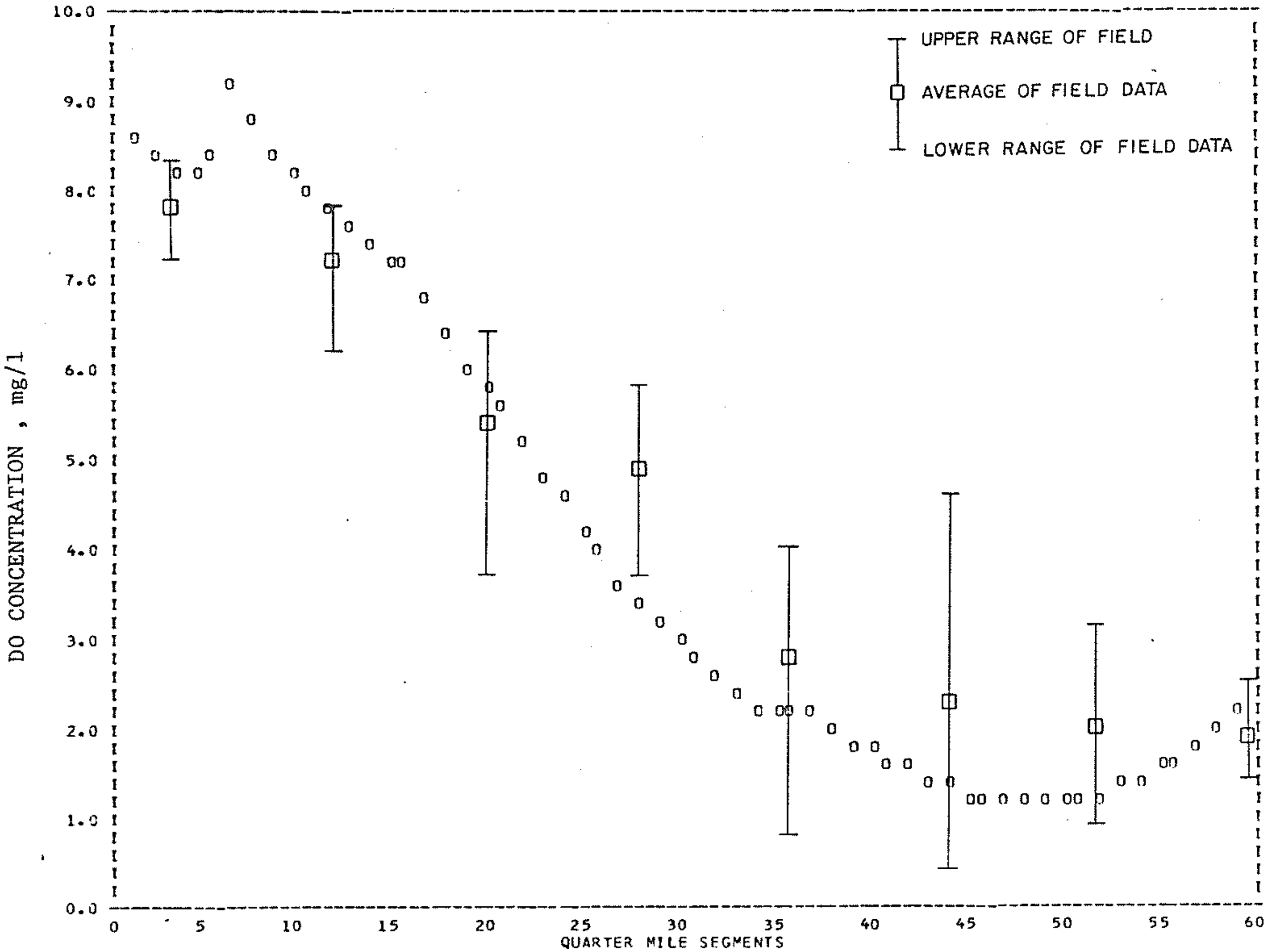

Fig. 4.6 1st High Flow Dissolved Oxygen Calibration

the flushing action of the previous period, the DO concentration was relatively high. Fig. 4.7 compares predicted and observed DO concentration for the period. Figs. 4.8 and 4.9 compare the predicted BOD_5 and NH_3-N concentration to field data values.

Verification under summer conditions is difficult due to the low DO values generally present. However, the T.W.Q.B. made a sampling run on August 14, 1973 and the reported values of DO are compared to predicted values in Fig. 4.10. The loads, discharges, and loading points used are the same as those used by the T.W.Q.B. for modeling this period.

The field DO values vary considerably with depth and are generally erratic, but even so the predicted values are within the range of values observed at five of the six sampling locations.

Overall, the model performed excellently predicting values very near observed values under a variety of conditions. Oxygen predictions in particular were very close to field data, thereby verifying the oxygen dynamics equations.

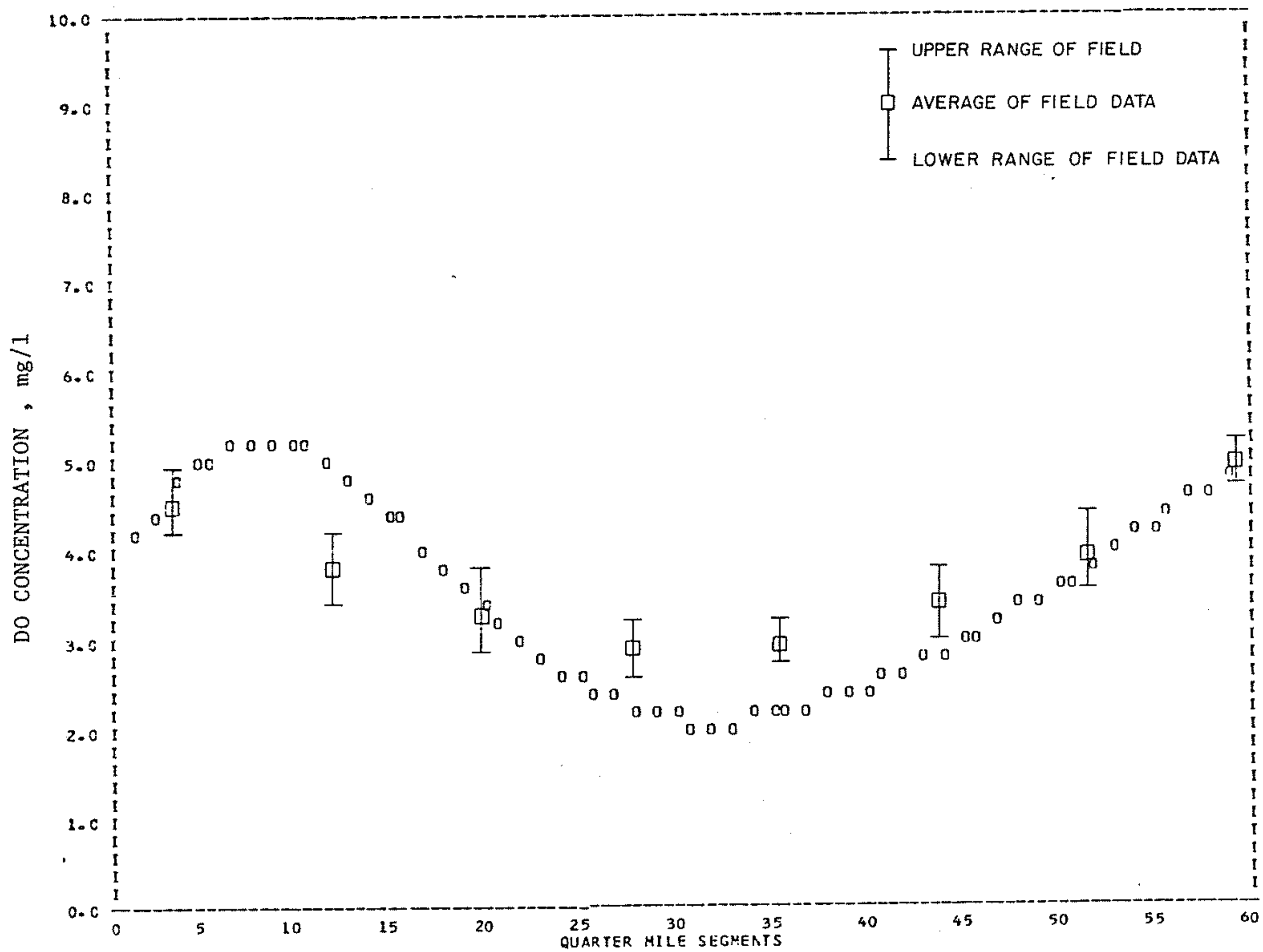

Fig. 4.7 2nd High Flow Dissolved Oxygen Calibration

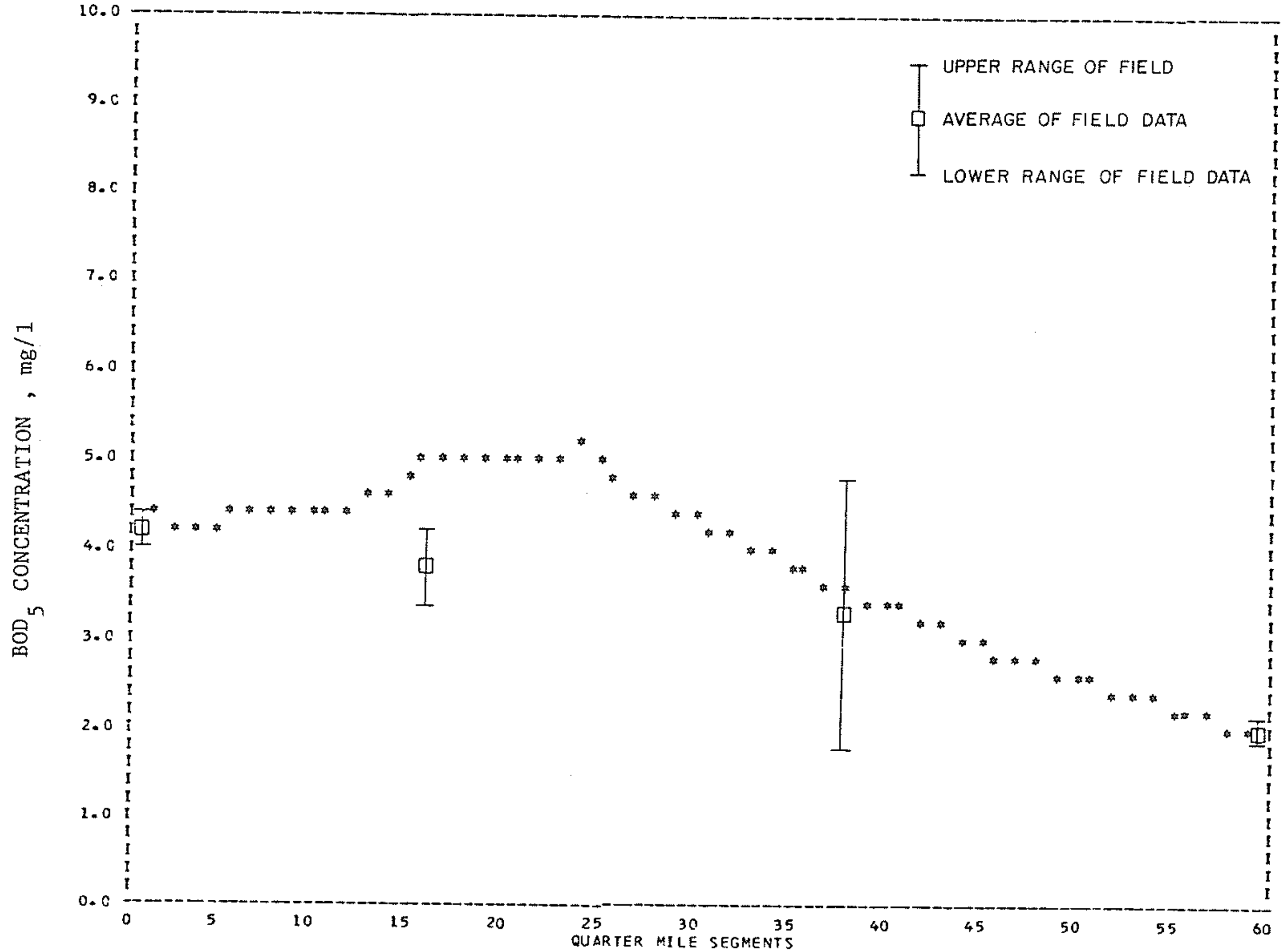

Fig. 4.8 High Flow BOD_5 Calibration

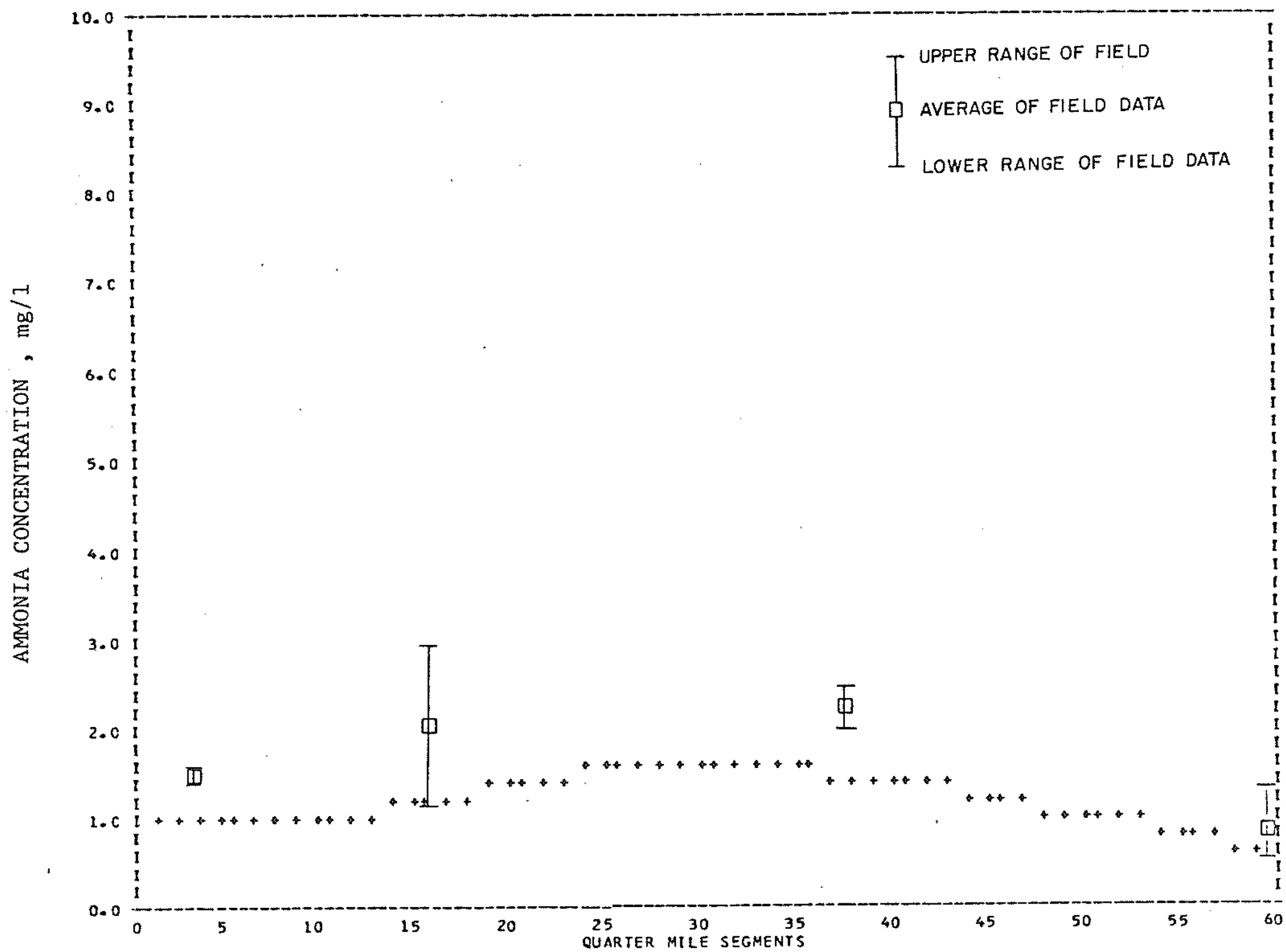

Fig. 4.9 High Flow Ammonia Calibration

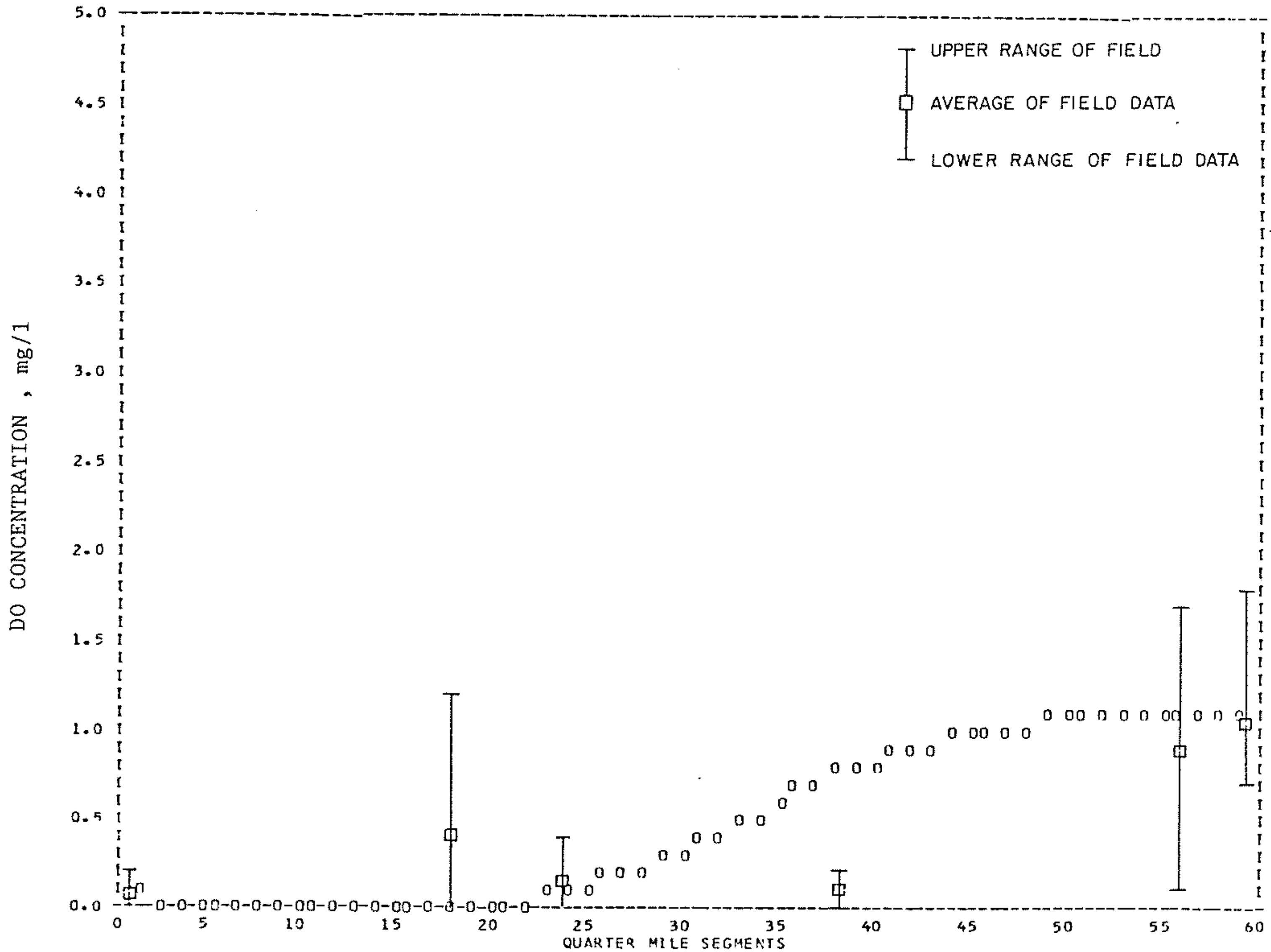

Fig. 4.10 2nd Low Flow Dissolved Oxyge Calibration

CHAPTER V

GENERAL DESIGN

In order to compare the four types of aeration systems, a general design that considers the amount of supplemental oxygen required and the aerator site locations is developed in this chapter.
Criteria of 2 mg/l and 4 mg/l DO are examined for the conditions requiring the greatest supplemental oxygen, i.e. summer, low flow conditions. Systems capable of maintaining criteria DO under these conditions are capable of maintaining criteria under all commonly occurring conditions.

Model Inputs

The T.W.Q.B. Galveston Bay Project[58] gives the following definition of low flow for the upper channel:

Excluding Waste Discharges 145 cfs

Including Waste Discharges 649 cfs

The T.W.Q.B. arrived at these low flow values by studying seven-day mean discharge records. The seven-day means are used to account for the "set up" that may be caused by winds, tides and other similar phenomena that have a distorting effect on daily flows. The waste discharge quantities are taken from the self-reporting system records.

The individual discharges are given in Appendix B . As shown on the excedance plot in Fig. 5.1, low flow excluding waste discharges

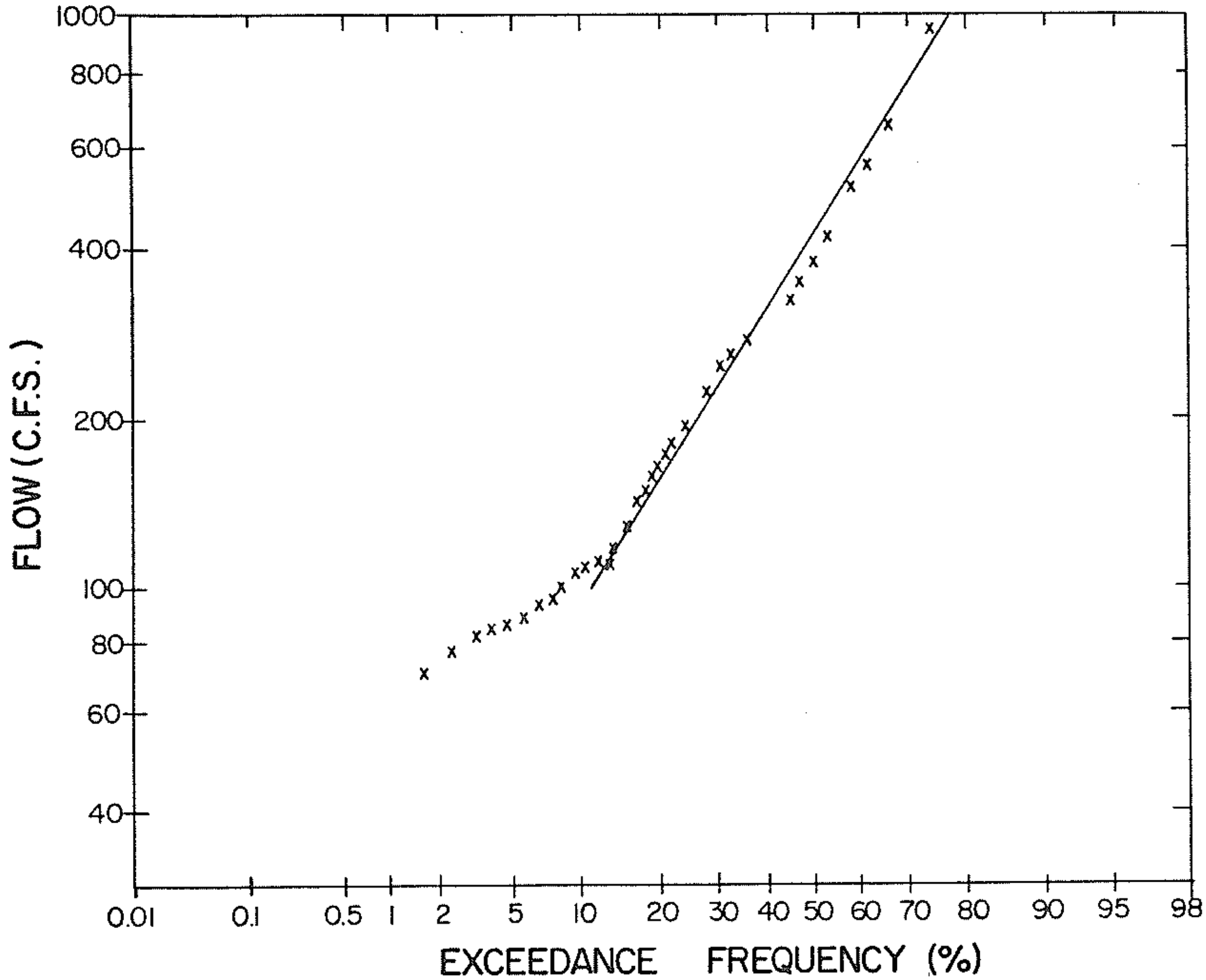

Fig. 5.1 Discharge Frequency

is not a rare occurrence, but is experienced 20 percent of the time.

The dispersion coefficient in tidal rivers has been modeled by several researchers, but models tend to be specific for a particular location and agreement between models is poor. Hydroscience, Inc.[11] studied salinity patterns in the ship channel during various flow conditions and estimated the dispersion coefficient for 145 cfs at 1200 ft^2/second. A dye study conducted in February 1973 by a team from Texas A&M University found the dispersion coefficient to vary from 708 ft^2/second to 1400 ft^2/second. Benson[28], using salinity values, estimated the dispersion coefficient to vary from 500 ft^2/second at the turning basin to 1000 ft^2/second at the monument. Trial model verification produced good results with Benson's values and they are selected.

Average widths, depths, surface areas, cross-sectional areas, and volumes for each segment were determined using Coastal and Geodetic Survey Map Number 590 (November, 1970, revision). The values are given in Appendix C .

Minimum System Capacity

The supplemental oxygen required to maintain a given DO criterion varies inversely with the number of aeration sites. Theoretically, the minimum system capacity required to maintain criteria DO is made up of many small units placed side by side throughout the length of the channel. This system is more efficient than a system consisting of a few large units for two reasons: 1) the driving force (C_s-C) at each aerator is maximized, and 2) "DO build-up" is minimized. "DO build-up", as used herein, refers to the mass of oxygen which must be maintained at the aeration site to satisfy criteria DO between sites. The cross-hatched area in Fig. 5.2 illustrates "DO build-up". The primary constraint on the system which produces this phenomenon is the rate of oxygen dispersion away from the aerator sites. Whipple, et al.[8] report greater longitudinal dispersion of dye from a diffuser header than would be expected from a point discharge and they attribute the increase to turbulent mixing at the point of release. This indicates less "DO build-up" may occur than indicated by using dispersion coefficients for point discharges; however, in the absence of complete research into the concept the more conservative point source dispersion coefficients are used.

To calculate the minimum supplemental oxygen required to maintain criteria, the model is modified so as to add oxygen in each segment, thus simulating a system of 60 aerators. The amount of oxygen required to maintain criteria in each segment is recorded and the total is equal to the minimum required oxygen. Because small segment lengths (0.25 miles) are used, "DO build-up" is minimized. The minimum oxygen required to maintain 2 mg/1 DO is 71,644 lb/day; the segmental requirements are shown in Fig. 5.3. To maintain 4 mg/1 DO, 133,965 lb/day are required and the segmental requirements are shown in Fig. 5.4. It should be noted that the two predominant peaks on Figs. 5.3 and 5.4 correspond to the mouths of Buffalo Bayou and Sims Bayou. Similar calculations were made for criteria of 1 mg/1, 3 mg/1, and 5 mg/1 and Fig. 5.5 illustrates

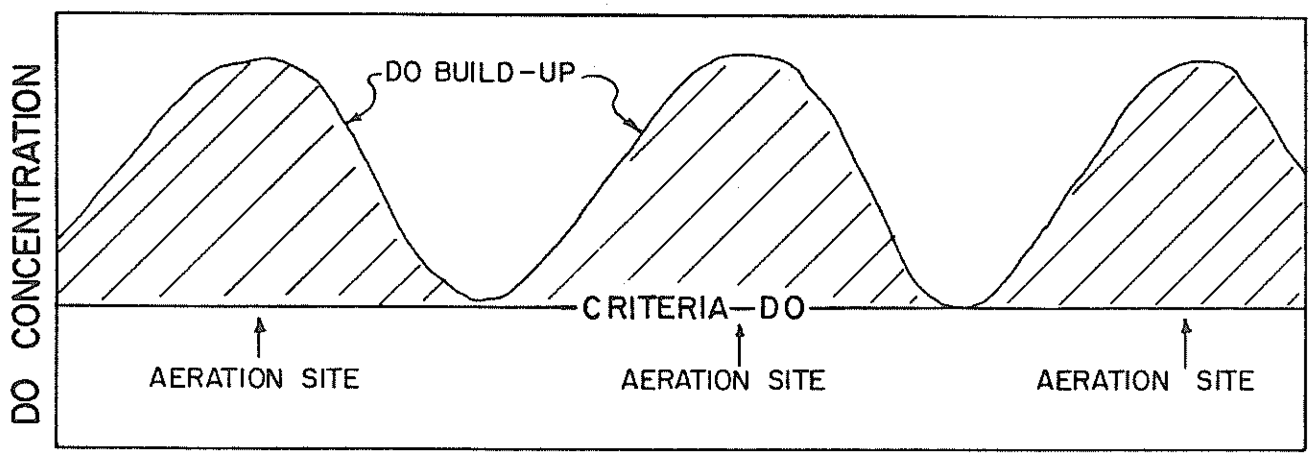

Fig. 5.2 Dissolved Oxygen Build-up

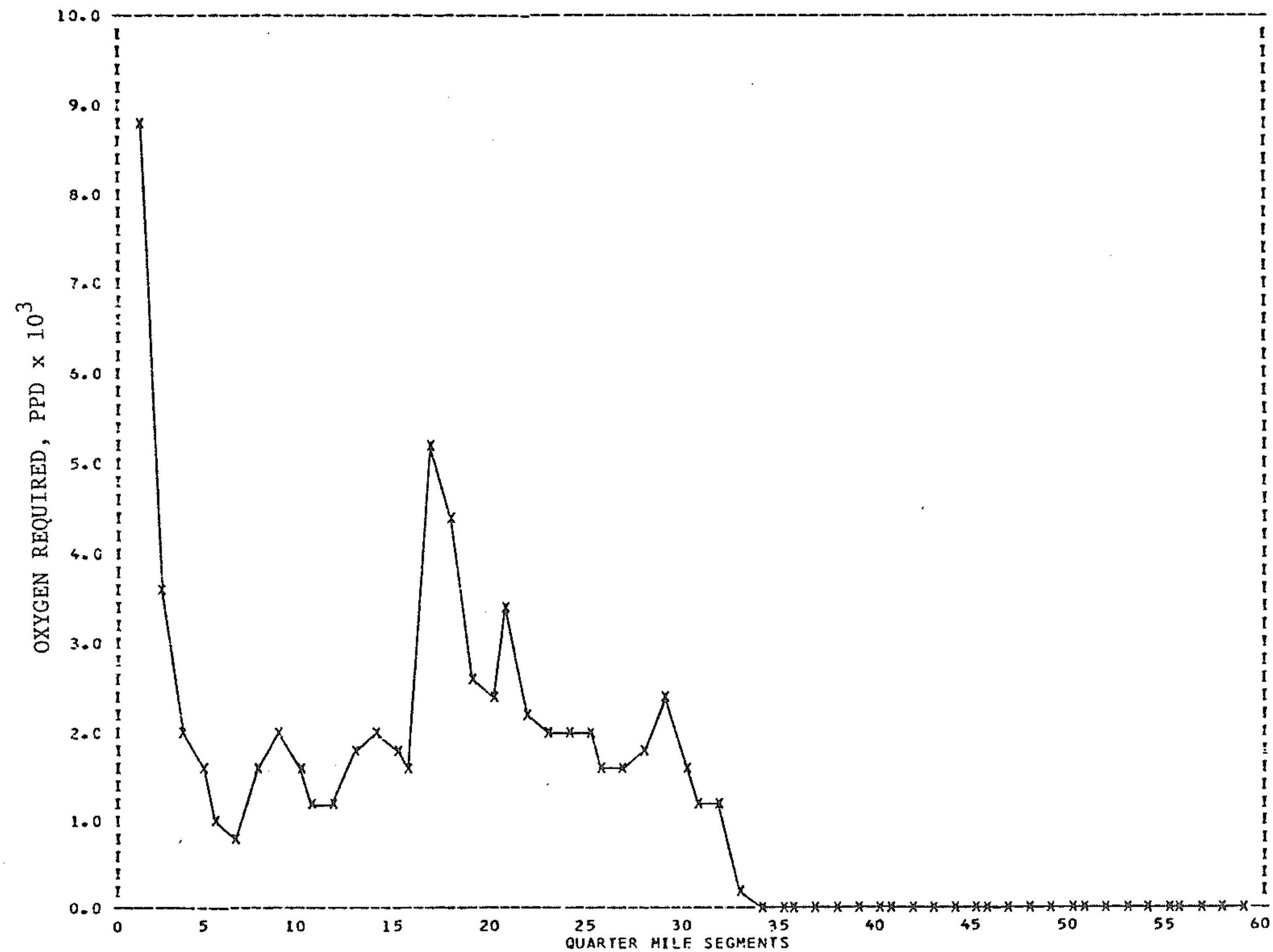

Fig. 5.3 Dissolved Oxygen Requirements for 2 mg/1 criteria

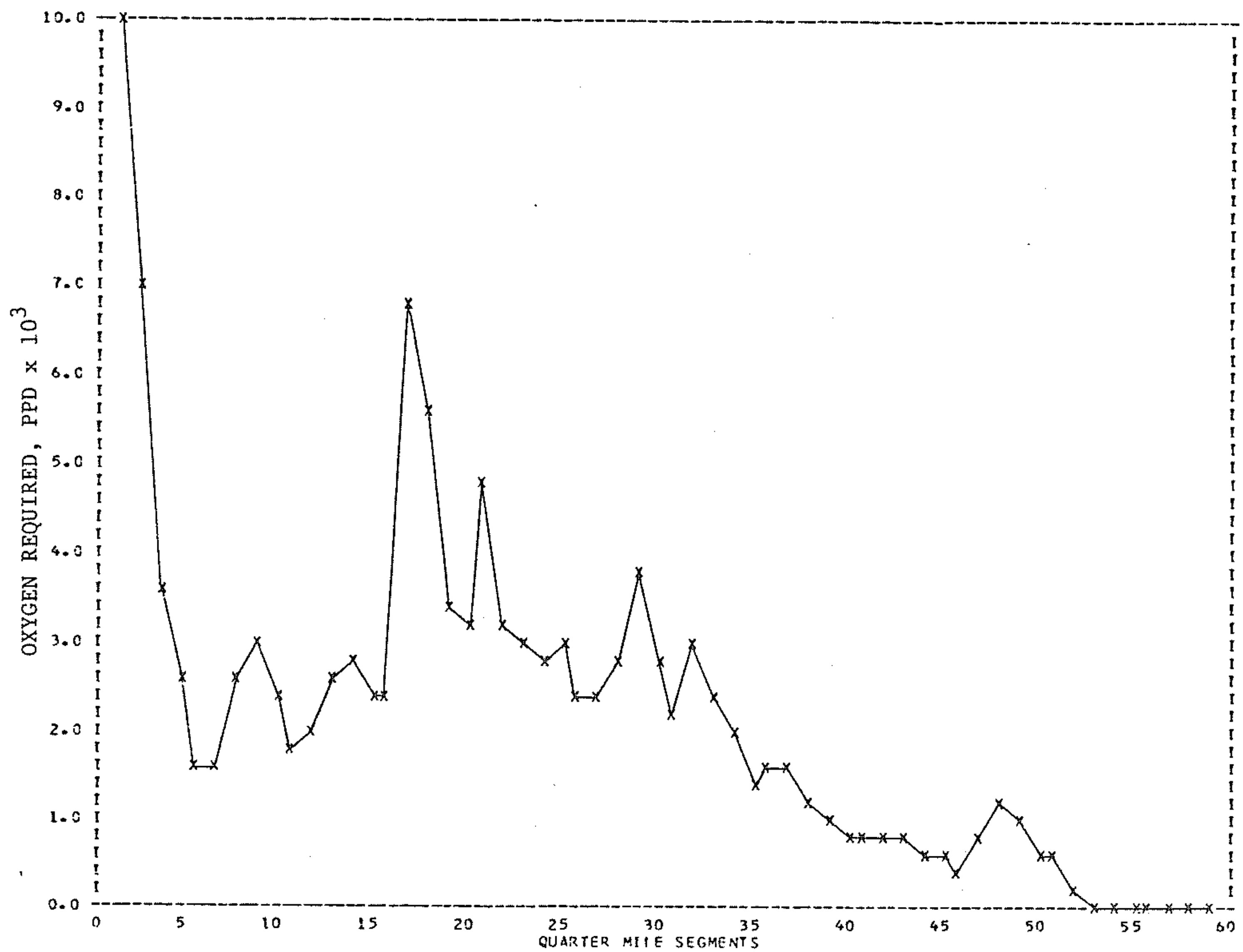

Fig. 5.4 Dissolved Oxygen Requirements for 4 mg/l criteria

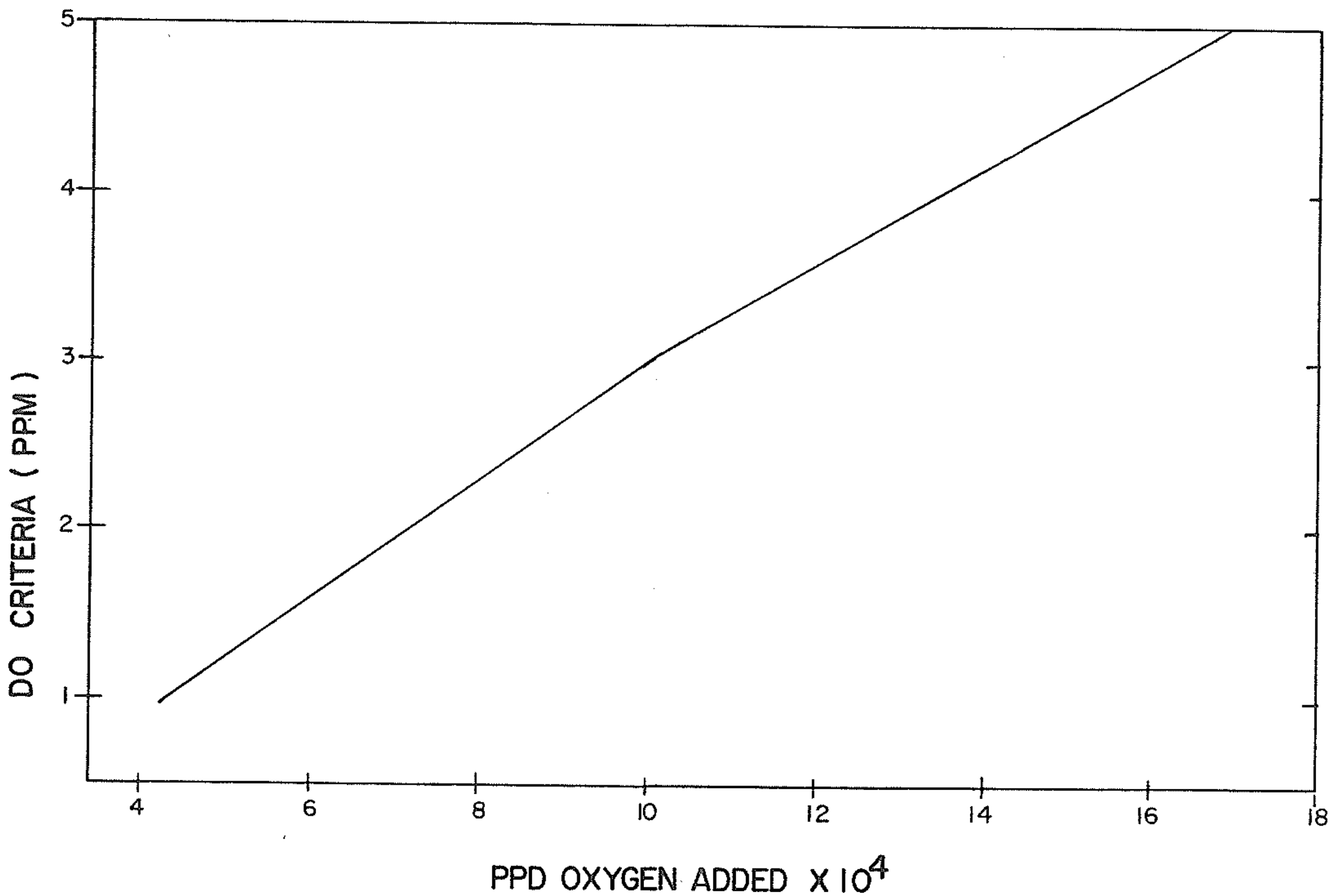

Fig. 5.5 Minimum Supplemental Oxygen Requirements

the minimum supplemental oxygen requirements for criteria of 1 to 5 mg/l.

Site Location

Figs. 5.3 (p. 55) and 5.4 (p. 56) show predominant peaks at segments 1 and 16 (river miles 24.5 and 21) and these will be used as initial aeration sites. By locating aerators in the segments where the most supplemental aeration is required "DO build-up" is minimized. This is a preliminary site selection and no consideration is given to the physical characteristics of the site. Setting a division line at one of the minimum values between the selected sites, such as at Segment 11, allows determination of the minimum system capacity required at each site by summing the oxygen required between divisions. This technique was used to evaluate aeration systems with 2, 3, 4, and 6 sites, and the oxygen requirements determined are presented in Table 5.1. Minimum system capacity is also calculated for 4 mg/l criteria and the values are presented in Table 5.1. Due to the increased oxygen required to maintain 4 mg/l DO, a system of seven aeration sites is evaluated for this condition. The division points were selected with consideration for minimizing "DO build-up" at each site, for oxygen requirements per segment, and to a lesser degree, for equalization of aerator capacity at each site. It should be noted that the divisions are only used to estimate oxygen requirements and do not in any way set limits on the actual oxygen required at a site.

Actual System Capacity

As explained previously, the actual system capacity is greater

TABLE 5.1
Minimum System Capacities

	Aerator Segment	Division Segment	minimum capacity lb. O_2/day 2 mg/l Criteria	4 mg/l
2	1	11	24,440	43,694
Sites	17		47,190	90,271
Total			71,630	133,965
3	1	11	24,440	43,694
Sites	17	23	31,080	42,268
	29		16,110	48,003
Total			71,630	133,965
4	1	5	16,181	30,547
Sites	9	11	8,259	13,147
	17	23	31,080	42,268
	29		16,110	48,003
Total			71,630	133,965
6	1	7	18,041	33,816
Sites	9	11	6,398	9,818
	14	16	8,591	12,356
	17	20	14,615	18,887
	21	26	13,512	19,462
	29		10,473	39,566
Total			71,630	133,965
7	1	7		33,876
Sites	9	11		9,818
	14	16		12,356
	17	20		18,887
	21	26		19,462
	29	40		29,553
	48			10,013
Total				133,965

than the minimum system capacity due to "DO build-up". Equipment efficiency affects the unit size required, but this is not to be confused with the amount of oxygen that must be transferred.

A trial and error solution is used to determine the actual required system capacity. The minimum required capacity for each site is taken as a starting point and the values are increased, being careful not to raise the maximum DO concentration at one aeration site much higher than at another, until the minimum DO concentration between sites is above the criteria. This procedure was used for 2, 3, 4, and 6 aeration sites and for 2 mg/l criteria and 3, 4, 6, and 7 aeration sites for 4 mg/l criteria. The results are presented in Table 5.2. Figs. 5.6 and 5.7 illustrate the oxygen requirements. As illustrated in Fig. 5.8 the required oxygen is reduced as the number of aeration sites increases. By comparing Tables 5.1 (p. 59) and 5.2 (p. 60) that portion of the capacity required to overcome "DO build-up" is calculated and presented in Fig. 5.9.

System Operating Capacity

The oxygen transfer capacities calculated thus far in this chapter are total system capacities capable of maintaining criteria DO under low flow summer conditions. During periods of less severe conditions the system will operate at less than total capacity in order to reduce operating and maintenance costs and extend equip   life. Control apparatus, such as a system of DO probes, are required to vary the aeration capacity, but design of such apparatus is beyond the scope of this study.

The required system capacity is primarily dependent on water

TABLE 5.2
Actual System Capacities

	Aerator Segment	actual capacity lb. O_2/day 2 mg/l Criteria	4 mg/l
2	1	30,000	
Sites	17	83,000	
Total		113,000	
3	1	30,000	60,000
Sites	17	56,000	60,000
	29	18,000	60,000
Total		104,000	180,000
4	1	19,000	40,000
Sites	9	9,000	14,000
	17	47,500	60,000
	29	18,000	60,000
Total		93,500	174,000
6	1	19,000	40,000
Sites	9	7,000	10,000
	14	9,000	13,000
	17	15,000	20,000
	21	14,500	22,000
	29	11,000	45,000
Total		75,500	150,000
7	1		40,000
Sites	9		10,000
	14		13,000
	17		20,000
	21		22,000
	29		31,500
	48		10,500
Total			147,000

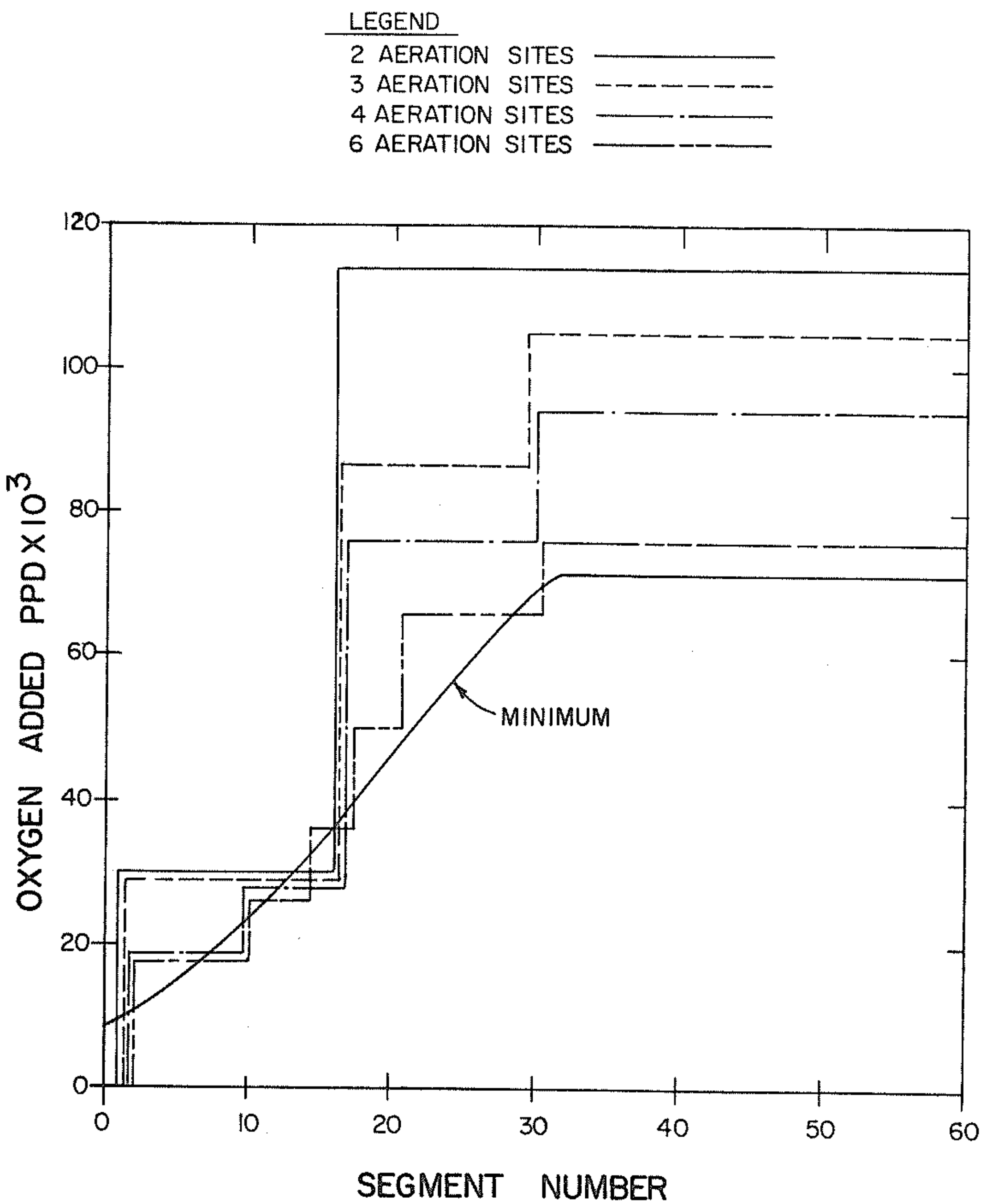

Fig. 5.6 Actual Oxygen Requirements per site for 2 mg/l criteria

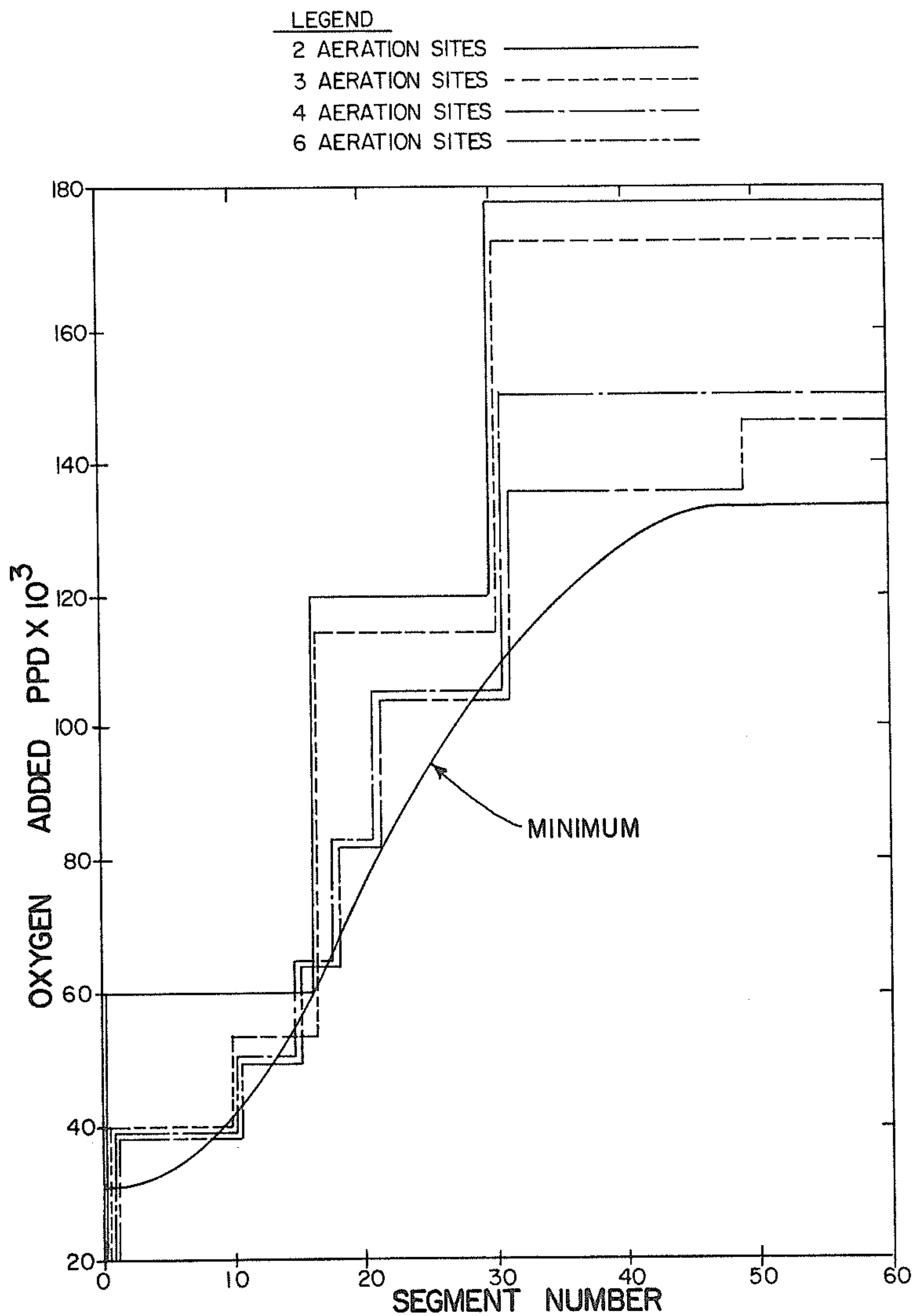

Fig. 5.7 Actual Oxygen Requirements per site for 4 mg/l criteria

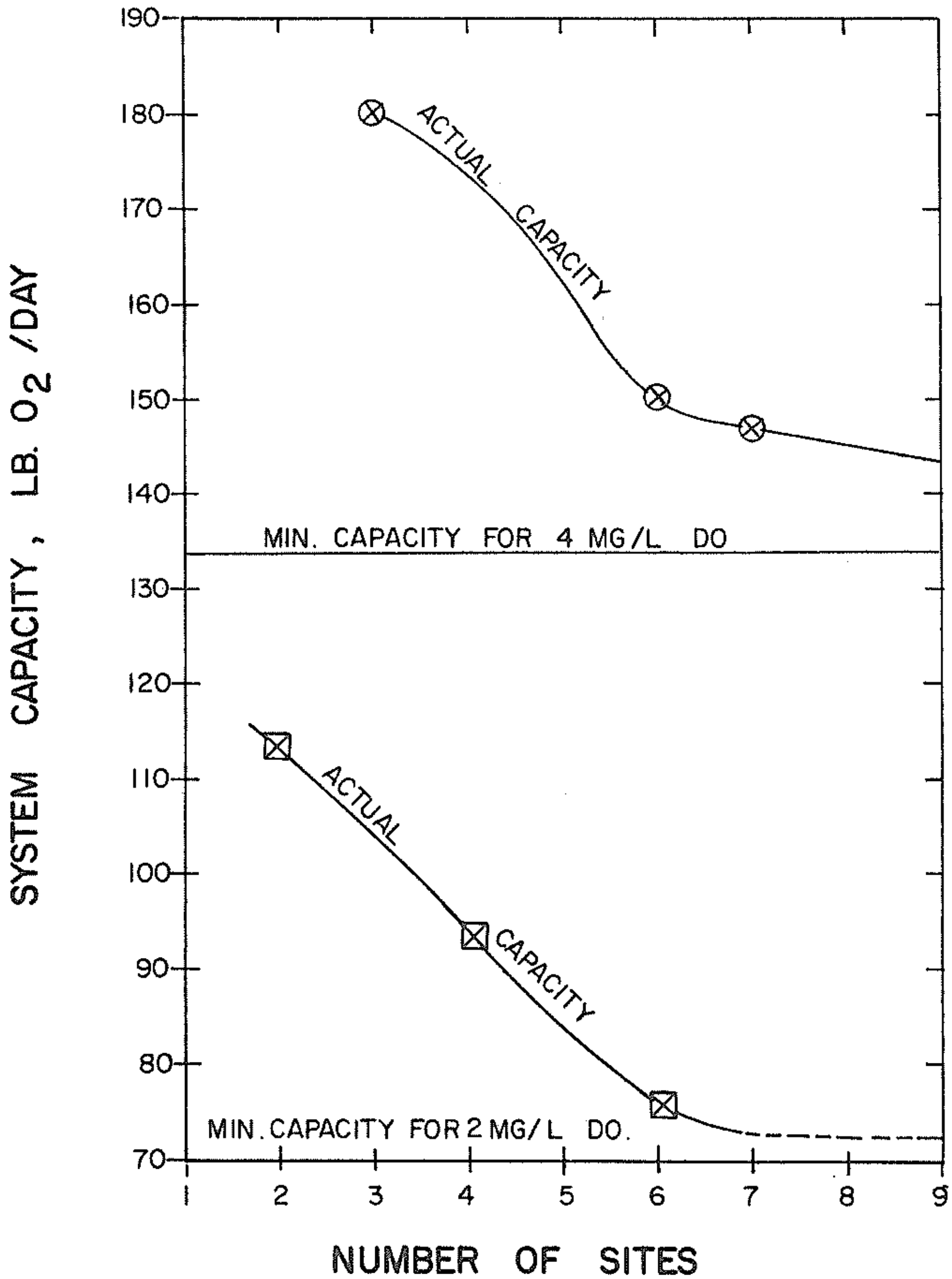

Fig. 5.8 Required System Capacity vs. Number of Sites

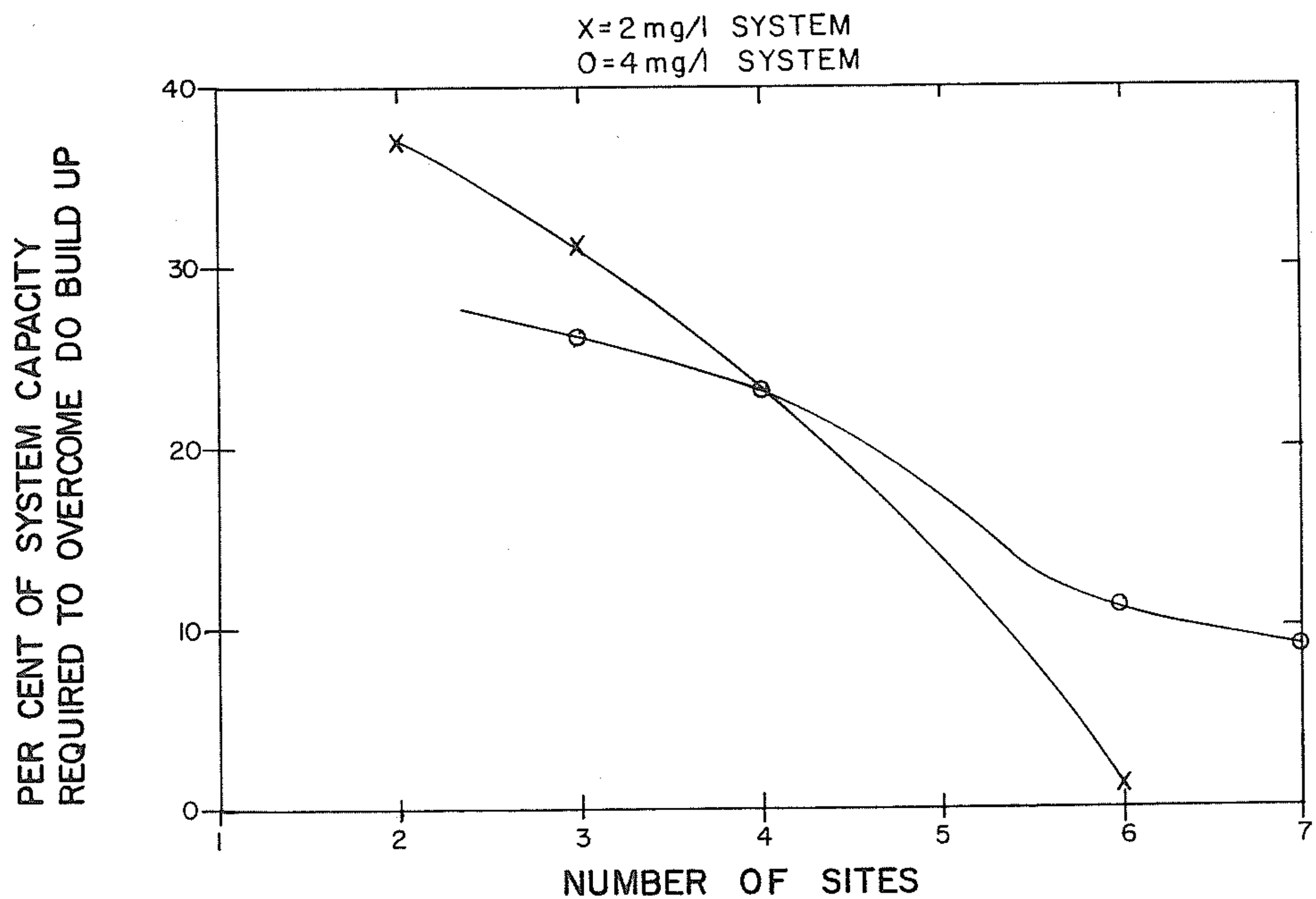

Fig. 5.9 System Capacity Required to Overcome Dissolved Oxygen Build-up

temperature and flow. The water temperature has substantial effect on decay rates and, to a lesser extent, on the reaeration rate. Stream flow determines the mass of oxygen supplied by the convergent bayous and affects the reaeration rate. By determining the discharge and temperature that represent the average conditions throughout the year, the average annual supplemental aeration capacity is determined.

Espey[59], using Texas A&M data, gives the temperature readings for the channel during 1968, 1969, and 1970. The average temperature during this time is 22.2° C.

In waterways with little flow regulation, such as the channel, the discharge is very erratic. The few high flow periods raise the mean discharge well above the discharge experienced fifty percent of the time. For this reason the median discharge, or 50 percent exceedance frequence discharge, is more representative of the average annual conditions. From Fig. 5.1(p.51), it is seen that median discharge is 440 cfs.

Using the average temperature, the median discharge and DO concentrations of the convergent bayous estimated from United States Geologic Survey Water Quality Records[56] the annual average operating capacity is calculated using the model. The values arrived at are compared to those determined earlier for summer, low flow conditions in Table 5.3. As shown in the table the average annual operating capacity is approximately 60 percent of the total capacity. This fraction is used in Chapter VI to calculate operating costs.

TABLE 5.3

Average Annual Operating Capacity

Criteria	Required Capacity Summer, Low Flow	Required Capcity Average Conditions	Average Operating Capacity
2 mg/1	71,664 PPD	42,710 PPD	60 %
4 mg/1	133,965 PPD	84,256 PPD	63 %

CHAPTER VI

SYSTEM COMPARISON

The purpose of this chapter is comparison of the four aeration system types on the basis of economic and physical feasibility. Alternative systems found to be significantly less attractive than the others are eliminated.

Economic Feasibility

An economic comparison is developed from the system capacities and number of sites determined in Chapter V. Capital costs are based on the capacity required to maintain criteria DO under the least favorable conditions. Operating cost estimates are made using the average annual operating capacity (60 percent of the total capacity) determined in Chapter V. A unit by unit economic analysis is not attempted, rather, general cost estimates for combinations of units, such as blowers plus diffuser headers, are made from the available literature. The estimates are brought to 1975 dollars by the Engineering News Record[60] cost index and combined into estimates of total system cost. This type of economic analysis provides adequate system comparison without requiring preliminary design of each system.

Land. The cost of land is not considered in the economic analysis. Purchase of land is an unlikely alternative due to the tremendous industrial value of shoreline footage. Leasing is a more likely alternative because the industries in the area are anxious to improve public relations and reduce treatment cost. In any case, it is estimated that all four system types require the same area (0.25 acres) per site and, therefore, the cost of land will not economically favor one system.

Oxygen Availability. The feasibility of both sidestream and diffused oxygenation depends on the availability of commercial oxygen. Presently oxygen is produced in air reduction plants of two types: 1) cryogenic (99.5 percent pure) and 2) pressure swing absorption or PSA (95 percent pure). Both processes produce relatively low pressure, gaseous oxygen which is either: 1) transported in a pipeline to the point of use, 2) liquefied in a separate refrigeration process, or 3) compressed into cylinders at about 3,000 pounds per square inch. Use of cylinder oxygen is not feasible for supplemental oxygenation due to the large storage capacity that is required.

Pipeline oxygen is available in the channel area from the Linde Division of Union Carbide or Big Three Industries, Inc. Both companies service Armco Steel at mile 17 on the channel, but neither company's pipeline extends further west than that point. Therefore, as can be seen on the map of Linde's pipeline shown in Fig. 6.1, the 7.5 miles of channel in the critical reach are not in close proximity to a pipeline. The cost of extending the pipeline further west is estimated at $100,000 per mile.[9,61]

Neither Linde nor Big Three have adequate excess capacity to supply an aeration system at this time, but it is common to expand the capacity of an oxygen plant to supply steady customers. It is assumed that such an expansion will be made if a supplemental aeration system requiring pipeline oxygen is implemented.

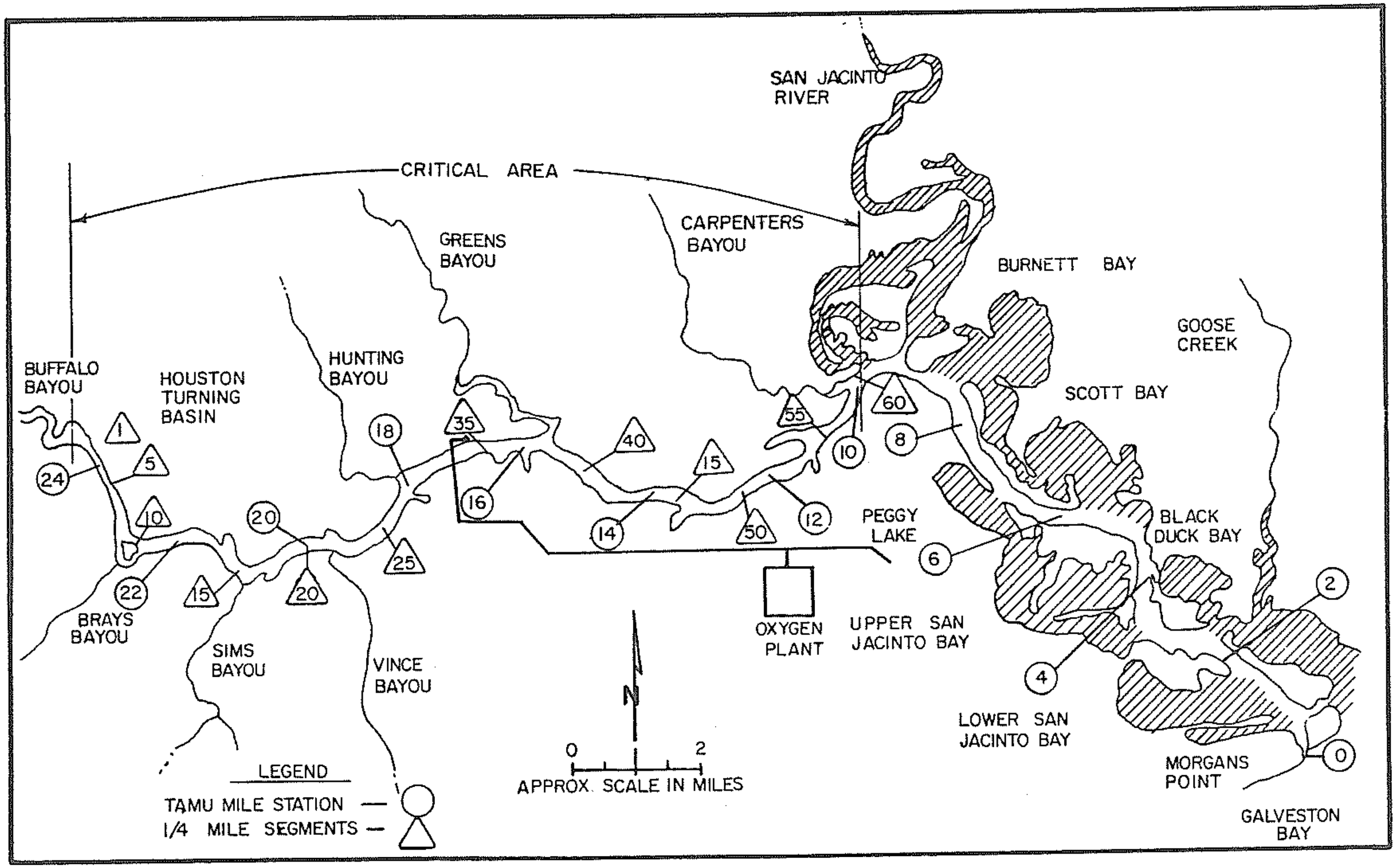

Fig. 6.1 Existing Oxygen Pipeline

Liquid oxygen is more expensive than gaseous pipeline oxygen due to the cost of refrigeration, but availability is good in the Houston area. On-site storage is provided by insulated pressure tanks which may be rented or purchased. The cost of storage tanks is given in Fig. 6.2.[62] Vaporizers are required to convert the liquid to gaseous oxygen just prior to injection.

An alternative to pipeline or liquid oxygen is on-site production. Either PSA or cryogenic oxygen plants can be purchased on a turnkey basis and used to supply an oxygenation system. Similar operations have recently come into use for sewage treatment plants. The capital cost associated with purchasing an oxygen plant as estimated by Linde Division[63] is shown in Fig. 6.3. As illustrated, PSA plants are more economical below 50 tons of oxygen produced per day and cryogenic plants become more economical above 50 tons per day. Both plant types include backup liquid oxygen storage facilities.

Oxygen supplied by any method is priced on a sliding scale dependent on consumption. Figure 6.4 illustrates the cost of liquid, pipeline, and on-site plant oxygen.[63] The cost of on-site plant oxygen includes only operation and maintenance costs, not amortized capital cost, or interest.

<u>Sidestream Oxygenation</u>. Olszewski[61] predicts up to 90 percent oxygen absorption from sidestream oxygenation with a system operating at 100 pounds per square inch gage (psig) and eductor nozzles at approximately 10 feet deep. Cooper[9] uses 75 percent absorption in his calculations assuming the system operates at 100 psig with eductor nozzles 40 feet deep. The more conservative value of 75 percent absorption is

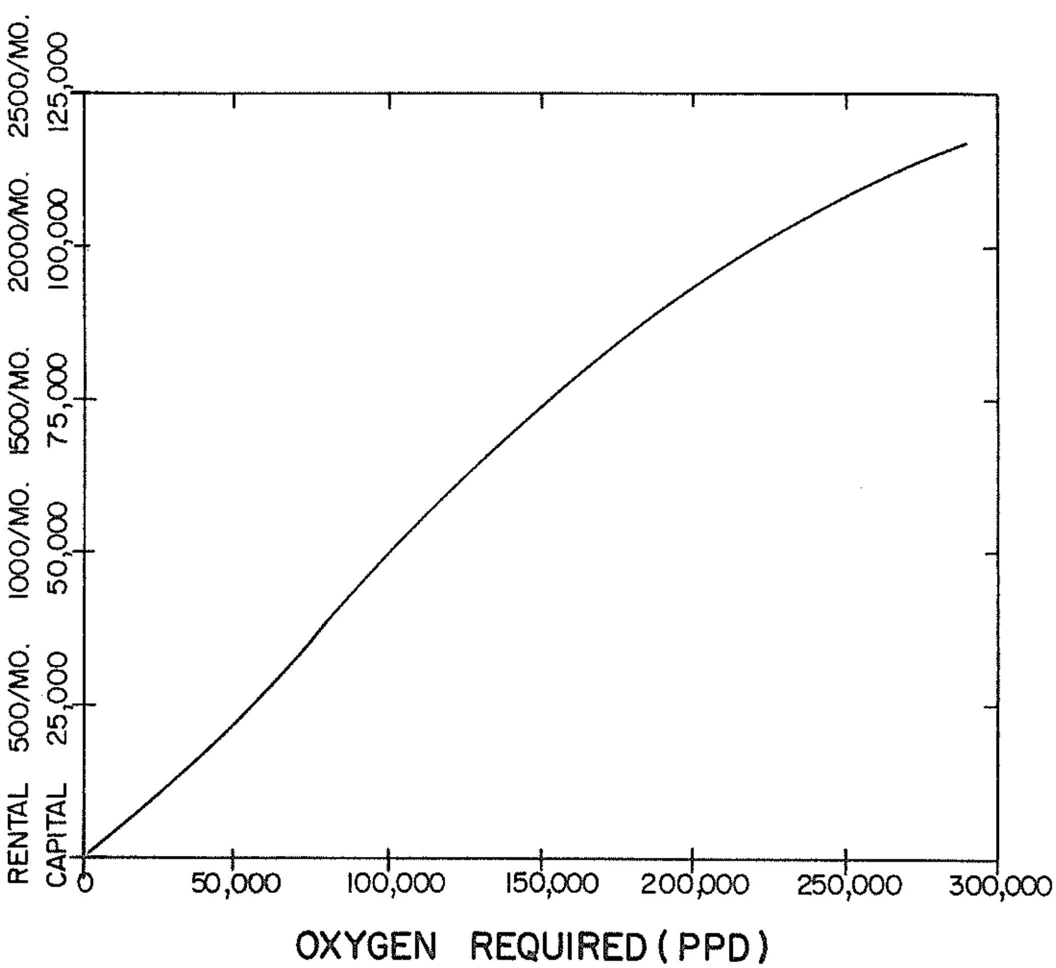

Fig. 6.2 Cost of Liquid Oxygen Storage Tanks

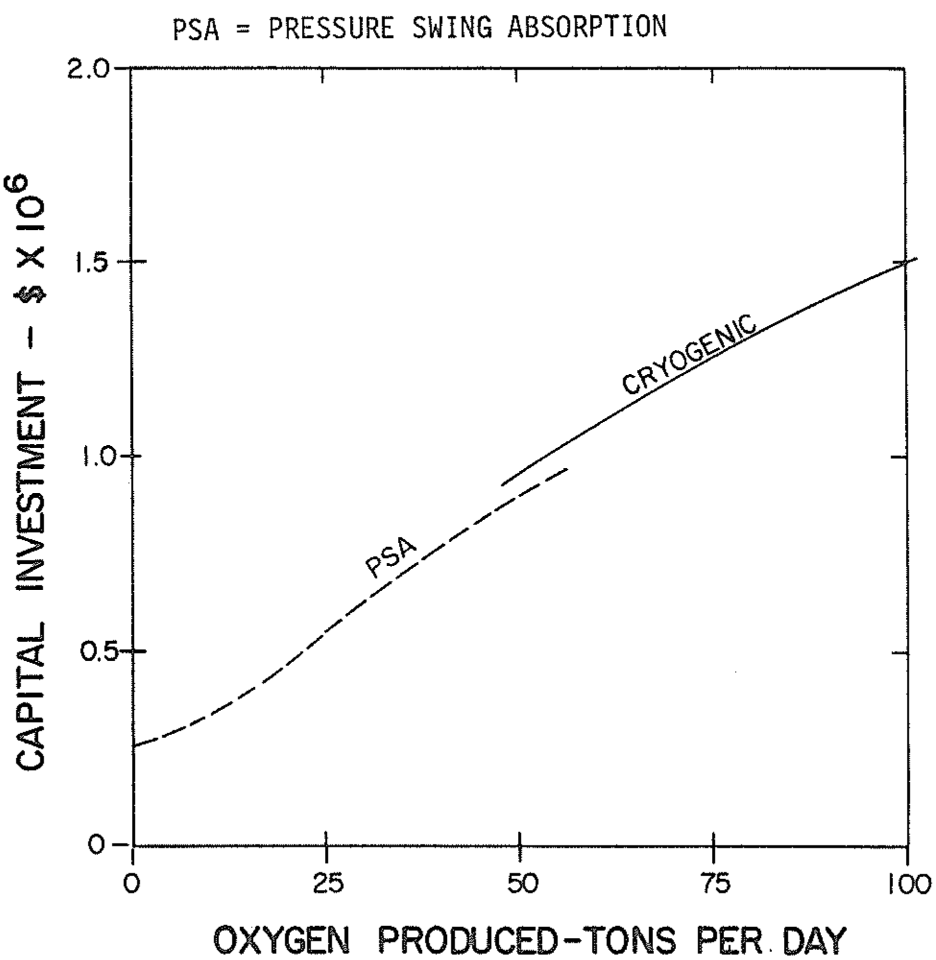

Fig. 6.3 Capital Cost of Oxygen Production Plant

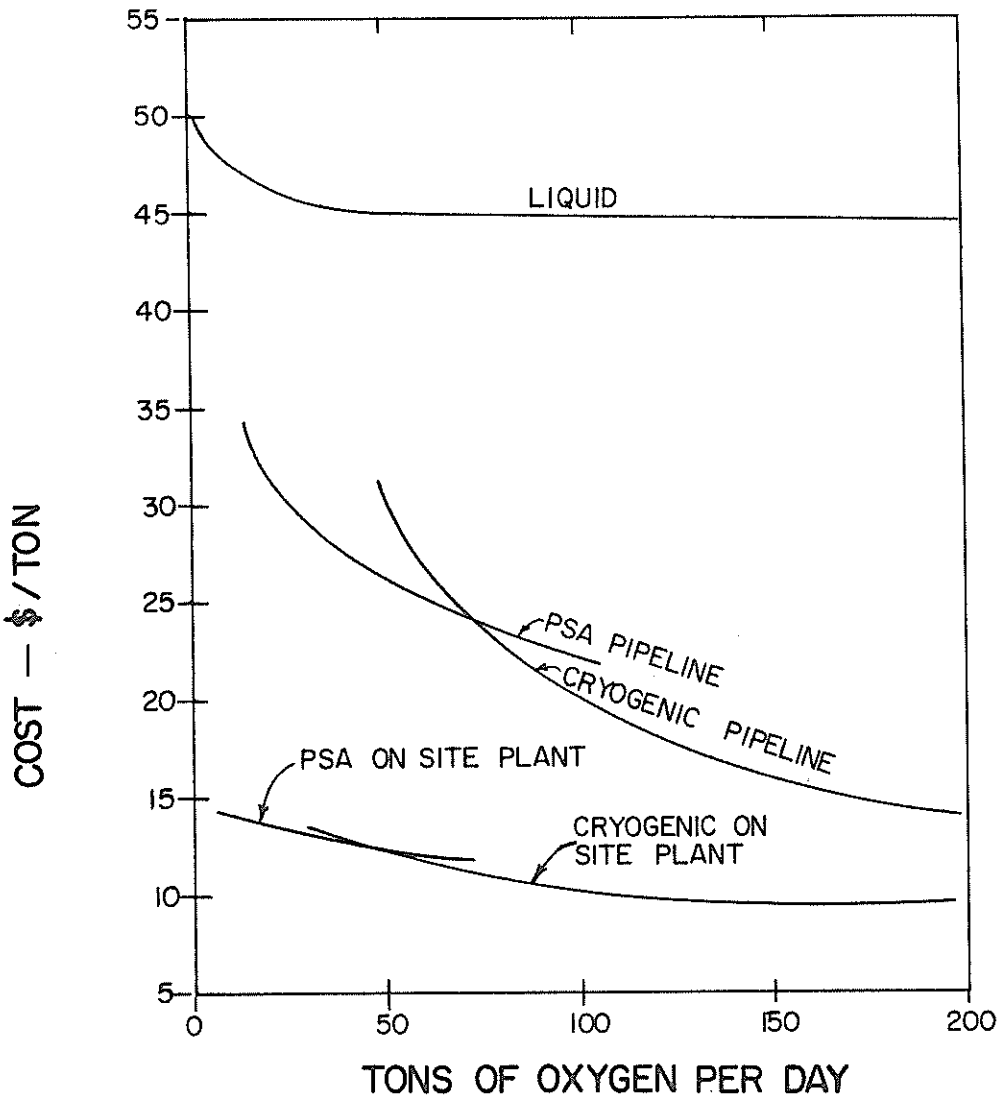

Fig. 6.4 Oxygen Cost

assumed herein. Using this value the oxygen injection capacities required for the channel are calculated and listed in Table 6.1.

The capital costs of sidestream aeration units, less oxygen supply equipment, are often estimated using a cost per unit capacity, such as dollars per ton of oxygen injected. Cooper[9] and Linde Division[62] use $5,000 per ton injected per day to estimate capital outlay and that figure is used herein. This value includes compressors to increase the oxygen pressure from 40 psig to 100 psig for injection.

Also included in the capital cost of sidestream aeration are site preparation, installation of electrical power supply equipment, and installation of electrical power supply equipment, and installation of a 15' x 15' metal building to house controls and electrical equipment. The costs used are as follows:

Site preparation	$14,000	per site
Metal building	4,500	per site
Power equipment	15,000	per site
Total	$33,500	per site

Oxygen supply equipment is another portion of the capital cost. If the system is supplied by pipeline oxygen, substantial capital outlay for pipeline construction is required. All of the alternative site arrangements require location of an aeration unit in segment 1, which is 7.5 miles from the nearest pipeline. Therefore, the capital cost of 7.5 miles of pipeline (7.5 miles x $100,000 per mile = $750,000) is included in each alternate site configuration. In addition, the capital

Table 6.1

Unit Capital Costs of Sidestream Aeration

Alternate	Segment	Actual Capacity PPD 2 mg/1	Actual Capacity PPD 4 mg/1	Oxygen Injected at 75% Absorption 2 mg/1	Oxygen Injected at 75% Absorption 4 mg/1	Unit Cost at $5000/T-day (K dollars) 2 mg/1	Unit Cost at $5000/T-day (K dollars) 4 mg/1
2	1	30,000		40,000		100	
Sites	17	83,000		111,000		277.5	
Total		113,000		151,000		377.5	
3	1	30,000	60,000	40,000	80,000	100	200
Sites	17	56,000	60,000	74,666	80,000	186.7	200
	29	18,000	60,000	24,000	80,000	60	200
Total		104,000	180,000	138,000	240,000	346.7	600
4	1	19,000	40,000	25,333	53,000	63.3	132.5
Sites	9	7,000	14,000	9,333	19,000	23.3	47.5
	17	47,500	60,000	63,333	80,000	158.3	200.0
	29	18,000	60,000	24,000	80,000	60	200.0
Total		91,500	174,000	121,999	232,000	305.0	580.0
6	1	19,000	40,000	25,300	53,300	63.3	133.250
Sites	9	7,000	10,000	9,300	13,330	23.3	33.250
	14	9,000	13,000	12,000	17,330	30.0	43.250
	17	15,000	20,000	20,000	26,670	50.0	66.75
	21	14,500	22,000	19,300	29,333	48.3	73.25
	29	11,000	45,000	14,600	60,000	36.5	150.00
Total		75,500	150,000	100,700	200,000	251.4	500.00
7	1		40,000		53,300		133.25
	9		10,000		13,300		33.25
	14		13,000		17,300		43.25
	17		20,000		26,660		66.75
	21		22,000		29,330		73.25
	29		31,500		42,000		105.00
	48		10,500		14,000		35.00
Total			147,000		196,000		490.00

cost of 0.25 miles of pipeline (0.25 miles x \$100,000 per mile = \$25,000) is allowed for connection of each site (except the site at segment 1) to main pipeline. The capital cost of a pipeline oxygen supply system is given in Table 6.2. Because \$100,000 per mile is a rough cost estimate no differentiation is made between the cost of a pipeline required to supply oxygen to a 2 mg/l system or a 4 mg/l system.

If a system supplied by liquid oxygen is chosen, storage tanks must be located at each site. Tanks may be either rented or purchased and the cost depends on the volume required. The tank volume chosen is three days storage capacity during peak usage. Using Fig. 6.2 (p. 72) the capital costs for a liquid oxygen system are calculated and given in Table 6.2.

The third oxygen supply system is on-site production. Using the maximum system capacity, the capital cost of turnkey oxygen plants is taken from Fig. 6.3 (p. 73) and listed in Table 6.2 for comparison with liquid and pipeline supply systems. Also included in the capital cost of each supply system is engineering contingency which is set at 15 percent of the initial capital costs.

Included in operation and maintenance cost of sidestream oxygenation are electrical cost, oxygen cost, labor cost, and replacement part cost. Electrical cost includes power to pump water through the pipe and power to produce the oxygen. The relationship between water pump horsepower and oxygen transfer can theoretically be as high as 3.0 lb. O_2 per horse-power-hour (lb. O_2/HP-hr), but 1.5 lb. O_2/HP-hr is a more realistic value.[61] Using 60 percent average annual operating capacity and assuming 1.5 lb. O_2

Table 6.2

Capital Costs of Oxygen Supply Equipment

Alternate	Segement	Pipeline $\$ \times 10^3$	Storage Tank $\$ \times 10^3$		Oxygen Plant $\$ \times 10^3$	
			2 mg/1	4 mg/1	2 mg/1	4 mg/1
2	1	387.5	65.0		450.0	
Sites	17	387.5	120.0		1,000.0	
Total		775.0	185.0		1,450.0	
3	1	267.0	65.0	105.0	450.0	750.0
Sites	17	267.0	100.0	105.0	750.0	750.0
	29	267.0	35.0	105.0	500.0	750.0
Total		801.0	200.0	315.0	1,700.0	2,250.0
4	1	206.0	35.0	75.0	300.0	550.0
	9	206.0	15.0	25.0	250.0	250.0
	17	206.0	90.0	105.0	600.0	750.0
	29	206.0	35.0	105.0	250.0	750.0
Total		826.0	175.0	310.0	1,400.0	2,300.0
6	1	146.0	35.0	75.0	250.0	550.0
Sites	9	146.0	15.0	17.0	250.0	250.0
	14	146.0	17.0	25.0	250.0	250.0
	17	146.0	30.0	45.0	250.0	300.0
	21	146.0	30.0	44.0	250.0	250.0
	29	146.0	20.0	90.0	250.0	600.0
Total		876.0	147.0	296.0	1,500.0	2,200.0
7	1	129.0		75.0		550.0
Sites	9	129.0		17.0		250.0
	14	129.0		25.0		250.0
	17	129.0		45.0		250.0
	21	129.0		44.0		250.0
	29	129.0		60.0		450.0
	48	129.0		20.0		250.0
Total		903.0		286.0		2,250.0

transferred per horsepower-hour, the annual electrical cost is calculated and reported in Appendix D.

The electrical costs associated with oxygen production are included in the cost of oxygen. This is true for all oxygen sources including on-site production. Appendix D contains the final cost sheets which list the electrical costs.

Oxygen costs are given in Fig. 6.4 (p.74). The cost of oxygen produced at the site included operation and maintenance cost. Annual oxygen cost is calculated using 60 percent of the plant capacity as the average annual operating capacity.

Labor is estimated at $20,000 per site and replacement part cost is estimated at 2 percent of the initial capital cost. Appendix D lists all operation and maintenance costs.

Fixed costs include interest and depreciation. Interest is calculated at 8 percent simple interest on the total initial investment. Depreciation is straight-line and the life of all sidestream systems is taken as 20 years[64] with a 10 percent salvage value at the end of 20 years. Fixed costs are also given in Appendix D .

The total annual costs of the alternates using sidestream oxygenation are given in Table 6.3 and the cost breakdown is given in Appendix D .

<u>Diffused Aeration</u>. In order to estimate the capital cost of diffused aeration systems, Patterson and Banker[65] relate the firm blower capacity to the capital cost. Figure 6.5 shows the graph used by Patterson and Banker. Seven per cent oxygen absorption is commonly assumed with diffuser systems,[66] and this figure is used to calculate the

TABLE 6.3

Total Annual Costs of Sidestream Oxygenation

		Number of Sites				
O_2 Source	Criteria	2	3	4	6	7
Pipeline	2 mg/l	$1,145,000	$1,105,000	$1,038,000	$ 975,000	
	4 mg/l		$1,553,000	$1,568,000	$1,461,000	$1,469,000
Purchased Liquid Tank	2 mg/l	$1,412,000	$1,348,000	$1,244,000	$1,123,000	
	4 mg/l		$2,182,000	$2,145,000	$1,951,000	$1,943,000
Rented Liquid Tank	2 mg/l	$1,387,000	$1,321,000	$1,222,000	$1,103,000	
	4 mg/l		$2,133,000	$2,098,000	$1,905,000	$1,898,000
On Site O_2 Production	2 mg/l	$1,193,000	$1,190,000	$1,097,000	$1,062,000	
	4 mg/l		$1,722,000	$1,721,000	$1,631,000	$1,645,000

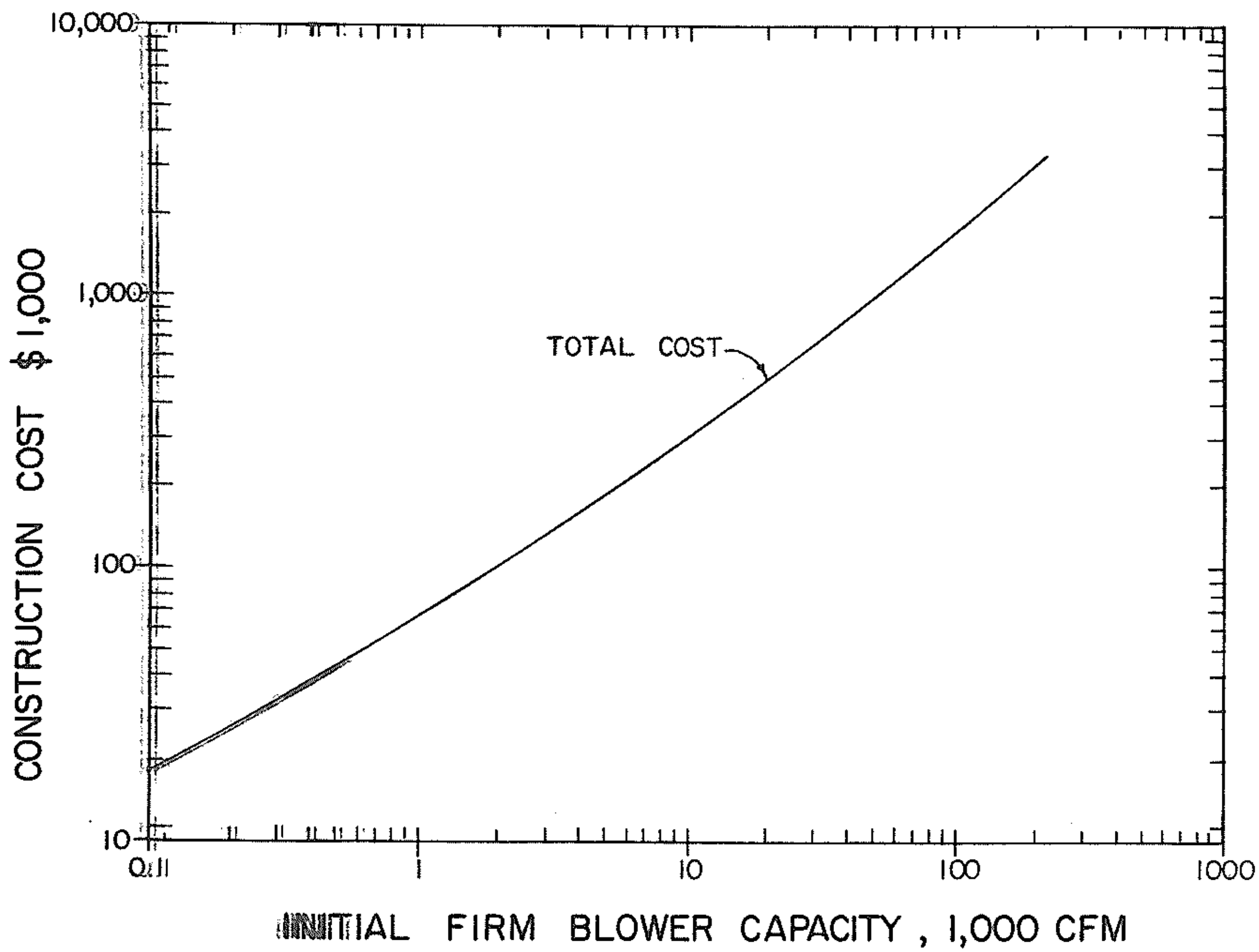

Fig. 6.5 Capital Cost of Diffused Aeration Systems

blower capacities given in Table 6.4. The capital cost of each alternate system is estimated from the 1971 Patterson and Banker graph and updated to 1975 costs by the Engineering News Record[60] cost index. The capital costs determined are given in Table 6.4.

The capital cost of electrical power equipment, a metal control building, and site preparation for a diffused aeration system is the same as that given for sidestream aeration, i.e. $33,500 per site. Engineering contingency is taken as 15 percent of the capital cost. The capital cost is shown on the final cost sheets in Appendix D .

Operation and maintenance costs, which include electrical cost, maintenance cost, and labor cost, are also given on the final cost sheets in Appendix D . Assuming 30 feet submergence, the required brake horsepower for blower drive is calculated with the equation used by Metcalf and Eddy, Inc.[66] At 2 cents per kilowatt-hour and an average annual operating capacity of 60 percent, the electrical costs are calculated and presented in Appendix D . Labor is, again, estimated at $20,000 per site and replacement parts are taken as 2 percent of the capital cost.

Interest is 8 percent and depreciation is straight-line for a 10-year life[64] and 10 percent salvage value. The total annual cost of each alternate diffused aeration system is shown in Table 6.5.

Diffused Oxygenation. A diffused oxygen system has features similar to those of sidestream aeration and diffused air systems. For this reason, a combination of the cost estimation techniques used previously is used here. The oxygen supply options described earlier in this

Table 6.4

Diffused Air Capital Costs

	Capacity CFM x 10^3		Capital Cost of Diffuser and Blower			
			1971 Cost $ x 10^3		1975 Cost $ x 10^3	
mg/1 DO	2	4	2	4	2	4
2	18.4		400		512	
Sites	50.9		1030		1318	
Total	69.3		1430		1830	
3	18.4	36.8	400	900	512	1152
Sites	34.4	36.8	800	900	1024	1152
	11.0	36.8	320	900	410	1152
Total	63.8	110.4	1520	2700	1946	3456
4	11.7	24.5	350	500	448	640
Sites	4.3	8.6	180	290	230	371
	29.0	36.8	740	900	947	1152
	11.0	36.8	320	900	410	1152
Total	56.0	116.7	1590	2590	2035	3313
6	11.7	24.5	350	500	448	640
Sites	4.3	6.1	180	220	230	282
	5.5	8.0	220	280	282	358
	9.2	12.3	300	390	384	499
	8.9	13.5	300	400	384	512
	6.7	27.6	250	700	320	896
Total	46.3	92.0	1600	2490	2048	3187
7		24.5		500		640
Sites		6.1		220		282
		8.0		280		358
		12.3		390		499
		13.5		400		512
		19.3		500		640
		6.4		250		320
Total		90.1		2540		3251

TABLE 6.5

Total Annual Cost of Diffused Aeration

	Number of Sites				
Criteria	2	3	4	6	7
2 mg/l	$1,036,000	$1,031,000	$ 968,000	$ 931,000	
4 mg/l		$1,742,000	$1,708,000	$1,609,000	$1,633,000

chapter (gaseous pipeline oxygen, gaseous oxygen produced at the site, and liquid oxygen stored in rented or purchased tanks) and evaluated for sidestream aeration are applicable to diffused oxygen and are examined as alternatives here.

Oxygen absorption efficiency with diffused oxygen systems in sewage treatment is expected to be approximately 15 percent.[25] The greater depth of submergence in the ship channel will improve system efficiency and the absorption is assumed to increase to 20 percent. Using the capacities given in Chapter V, the system capacities required with 20 percent absorption are calculated and given on Table 6.6. Oxygen diffuser units are, for cost estimation purposes, the same as air diffuser units and the Patterson and Banker[67] curve shown in Fig. 6.5 (p.84) is used to estimate the capital cost. However, the Patterson and Banker curve includes blower and blower housing cost. Reap[67] modified the Patterson and Banker curve to exclude the capital cost of blowers and blower housing and his curve is shown in Fig. 6.6. Using this curve and the capacities listed in Table 6.6, the capital cost of an oxygen diffuser system is calculated and shown on Table 6.6. This cost is then updated to 1975 cost with the Engineering News Record[60] cost index and listed on Table 6.6.

The oxygen supply equipment for a diffused oxygen system is the same as that of a sidestream oxygen system and the capital cost is the same. The capital cost for an oxygen pipeline, liquid storage tanks, and an oxygen production plant are given on Table 6.2 (p.78). These costs plus the cost of site preparation, electrical power equipment, control buildings (as before), and the diffuser cost shown in Table 6.6

Table 6.6

Diffused Oxygen Unit Capital Cost

	Capacity ft 3/m in $O_2 \times 10^3$		Capital Cost $\times 10^3$ excld. Bld.		1975 Costs $\times 10^3$	
	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l
2	1.35		48		61.4	
Sites	3.73		60		77	
Total	5.03		108		138.4	
3	1.35	2.70	48	50	61.4	64
Sites	2.52	2.70	45	50	58	64
	.81	2.70	22	50	28	64
Total	4.68	8.10	115	150	147.4	192
4	.86	1.80	23	38	29	49
Sites	.35	.63	13	20	17	26
	2.14	2.70	41	50	52	64
	.81	2.70	22	50	28	64
Total	4.16	7.83	99	158	126	203
6	.86	1.80	23	38	29	49
Sites	.35	.45	13	17	17	22
	.41	.58	16	18	21	23
	.67	.90	20	24	26	31
	.65	1.00	20	26	26	33
	.50	2.00	17	40	22	51
Total	3.44	6.73	109	163	141	209
7		1.80		38		49
Sites		.45		17		22
		.58		18		23
		.90		24		31
		1.00		26		33
		1.04		31		40
		.47		16		20
Total		6.24		170		218

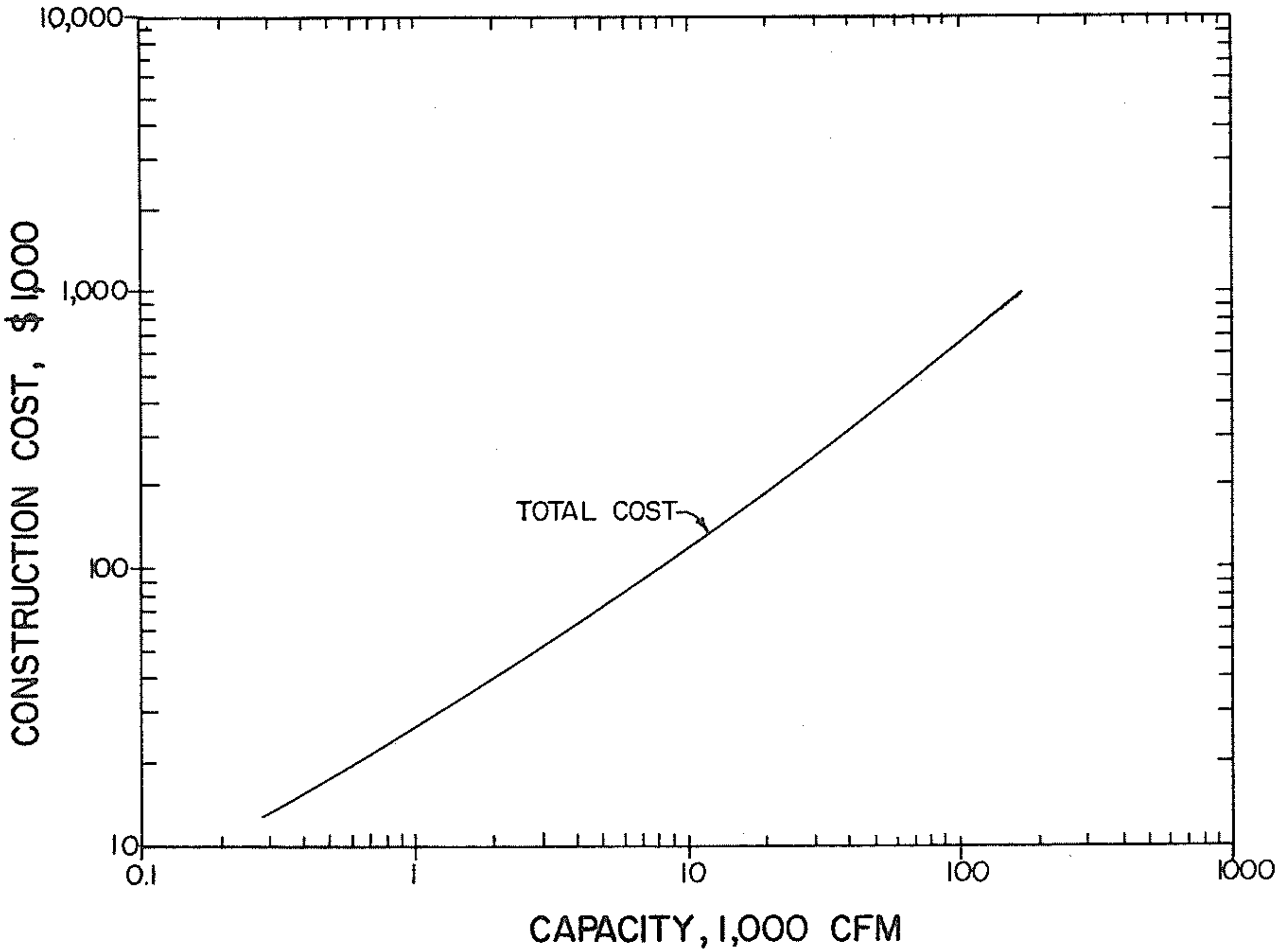

Fig. 6.6 Capital Cost of Diffusers

make up the initial capital cost. Engineering contingency is set at 15 percent and completes the capital cost (Appendix D).

Operation and maintenance cost includes oxygen, labor, replacement parts, electricity and, for one alternative, oxygen tank rental. Oxygen cost is the same as that used for sidestream aeration and is given on Fig. 6.4 (p. 74). Using the average annual capacities and Fig. 6.4 (p. 74) the oxygen costs are calculated (Appendix D).

Annual labor costs are estimated at $20,000 per site and replacement part costs are assumed to be 2 percent of the initial capital cost. Electrical costs incurred in oxygen production are included in oxygen cost.

The system is estimated to have a 15-year life[64] and depreciation is straight-line. Salvage value is assumed to be 10 percent of the initial capital cost. An itemization of these costs is given on the final cost sheets in Appendix D . The annual cost of each alternate diffused oxygen system is given in Table 6.7.

Surface Aeration. The capital cost of a surface aeration system is related to installed horsepower in the same manner that diffused aeration capital cost is related to firm blower capacity. The graph developed by Patterson and Banker[65] illustrating this relationship is given in Fig. 6.7. Manufacturers of surface aeration units often advertise efficiencies up to 4 lbs. of oxygen transferred per horsepower hour (lb. O_2/HP-hr) but in practice 2 lb. O_2/HP-hr is more typical.[64,66] Assuming an efficiency of 2 lb. O_2/HP-hr and using the oxygen requirements given in Chapter V, the horsepower requirements are calculated and shown in Table 6.8. Also given in Table 6.8 are the 1971 capital costs taken

Table 6.7

Total Annual Cost of Diffused Oxygenation

		Number of Sites				
O_2 Source	Criteria	2	3	4	6	7
Pipeline	2 mg/l	$1,167,000	$1,131,000	$1,134,000	$1,132,000	
	4 mg/l		$1,560,000	$1,549,000	$1,439,000	$1,449,000
Purchased Liquid Tank	2 mg/l	$2,922,000	$2,730,000	$2,442,000	$2,098,000	
	4 mg/l		$4,631,000	$4,511,000	$3,970,000	$3,923,000
Rented Liquid Tank	2 mg/l	$2,890,000	$2,696,000	$2,381,000	$2,073,000	
	4 mg/l		$4,577,000	$4,520,000	$3,920,000	$3,874,000
On Site O_2 Production	2 mg/l	$1,158,000	$1,165,000	$1,047,000	$1,046,000	
	4 mg/l		$1,711,000	$1,707,000	$1,595,000	$1,609,000

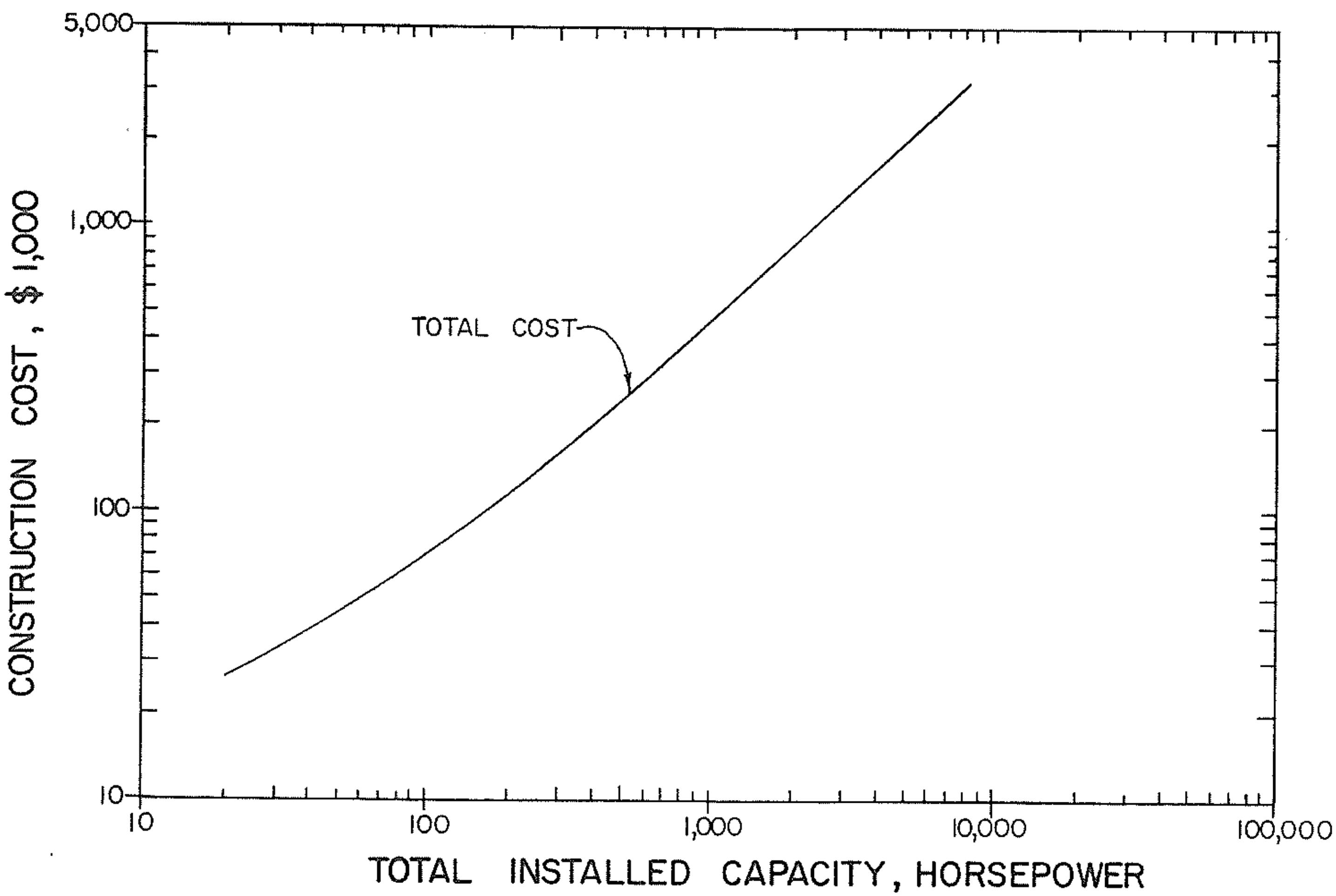

Fig. 6.7 Capital Cost of Surface Aerators

TABLE 6.8

Surface Aeration Capital Cost

	Horse-Power		Capital Cost Units 1971 x 10^6		Capital Cost 1975 x 10^6	
	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l
2	625		.3		.384	
Sites	1729		.75		.96	
Total	2354		1.05		1.34	
3	625	1250	.3	.53	.38	.68
Sites	1166	1250	.5	.53	.64	.68
	375	1250	.17	.53	.22	.68
Total	2166	3750	.97	1.6	1.24	2.05
4	396	833	.2	.38	.26	.49
Sites	146	292	.09	.15	.10	.19
	990	1250	.45	.53	.58	.68
	375	1250	.18	.53	.23	.68
Total	1906	3625	.92	1.59	1.18	2.04
6	396	833	.2	.38	.26	.49
Sites	146	208	.09	.12	.12	.15
	188	271	.12	.15	.15	.19
	312	416	.16	.20	.20	.26
	302	458	.16	.23	.20	.29
	229	938	.12	.41	.15	.52
Total	1573	3125	.85	1.49	1.09	1.91
7		833		.38		.49
Sites		208		.12		.15
		271		.15		.19
		416		.20		.26
		458		.23		.29
		656		.31		.39
		219		.12		.15
Total		3063		1.51		1.93

from the Patterson and Banker[65] graph and the 1975 costs as updated by the Engineering News Record[60] cost index.

The total cost of site preparation, installation of electrical power equipment, and a metal building is, again, \$33,500 per site. The initial capital cost and engineering contingency for each alternate surface aeration system are given in Appendix D .

Also given in Appendix D is the itemized operation and maintenance cost. The horsepower requirements listed in Table 6.8 (p. 91) and the average annual operating capacity are used to calculate the electrical cost (assuming \$0.02/Kilowatt-hour). Labor is estimated at \$20,000 per site, and replacement parts are estimated at 2 percent of the initial capital cost.

Interest is 8 percent and depreciation is straight-line. The life expectancy of surface aerators is somewhat less than that of other aeration units and is assumed to be 5 years[64] with a salvage value of 10 percent of the original capital cost. The total annual cost of surface aeration is shown on Table 6.9.

Economic Summation. The annual costs of each of the alternatives including all variations of oxygen supply equipment are plotted on Fig. 6.8 and Fig. 6.9. Annual cost decreases as the number of sites selected increase for all equipment types. However, this trend may not hold if land cost is included. The least expensive alternatives examined are those using surface aeration equipment and the most expensive are those using diffused liquid oxygen with either purchased or rented oxygen storage tanks. Despite the economic trends shown in Fig. 6.8, no

TABLE 6.9

Total Annual Cost of Surface Aeration

	Number of Sites				
Criteria	2	3	4	6	7
2 mg/1	$743,000	$ 734,000	$ 710,000	$ 701,000	
4 mg/1		$1,175,000	$1,189,000	$1,141,000	$1,169,000

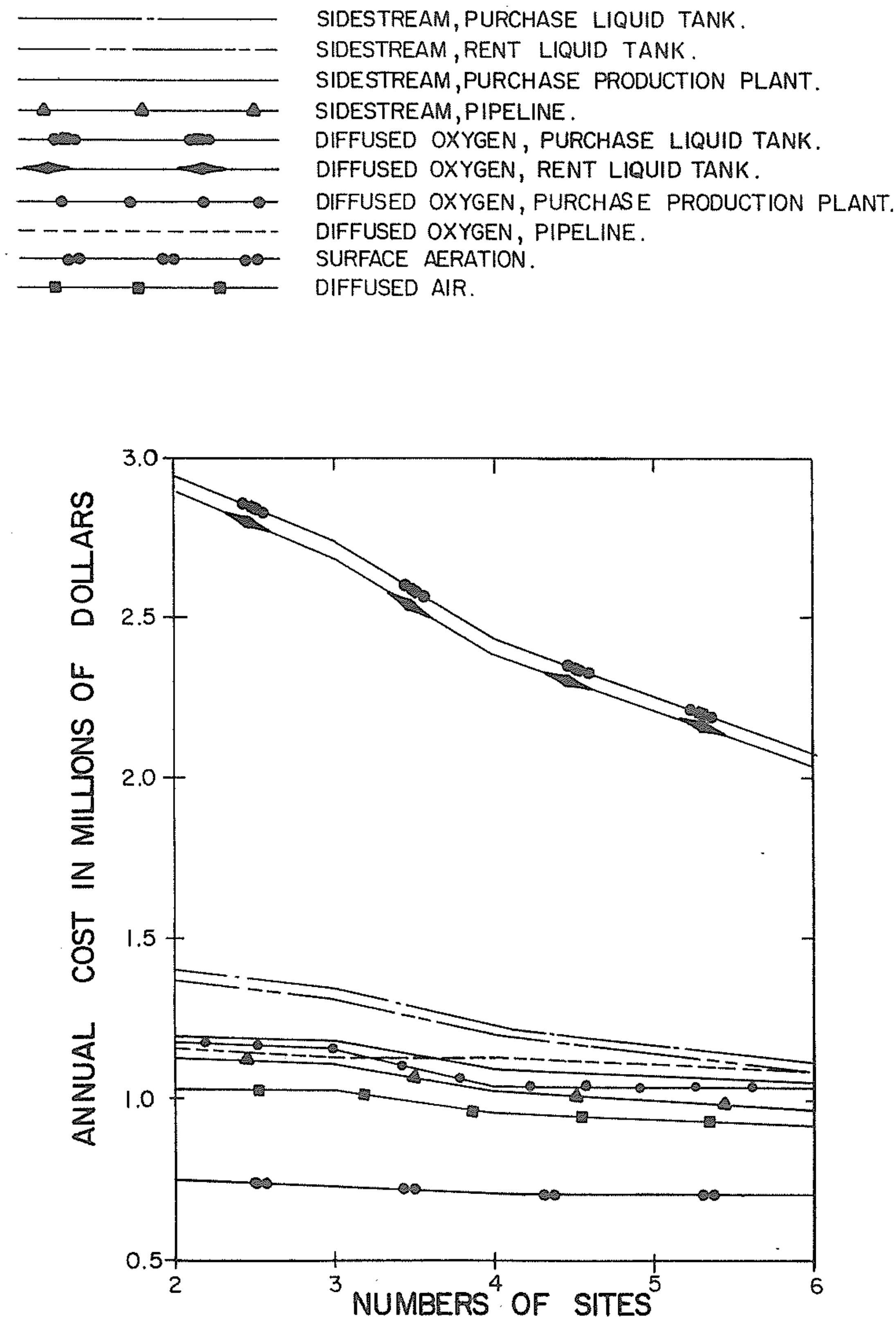

Fig. 6.8 Annual Cost of 2 mg/l Systems

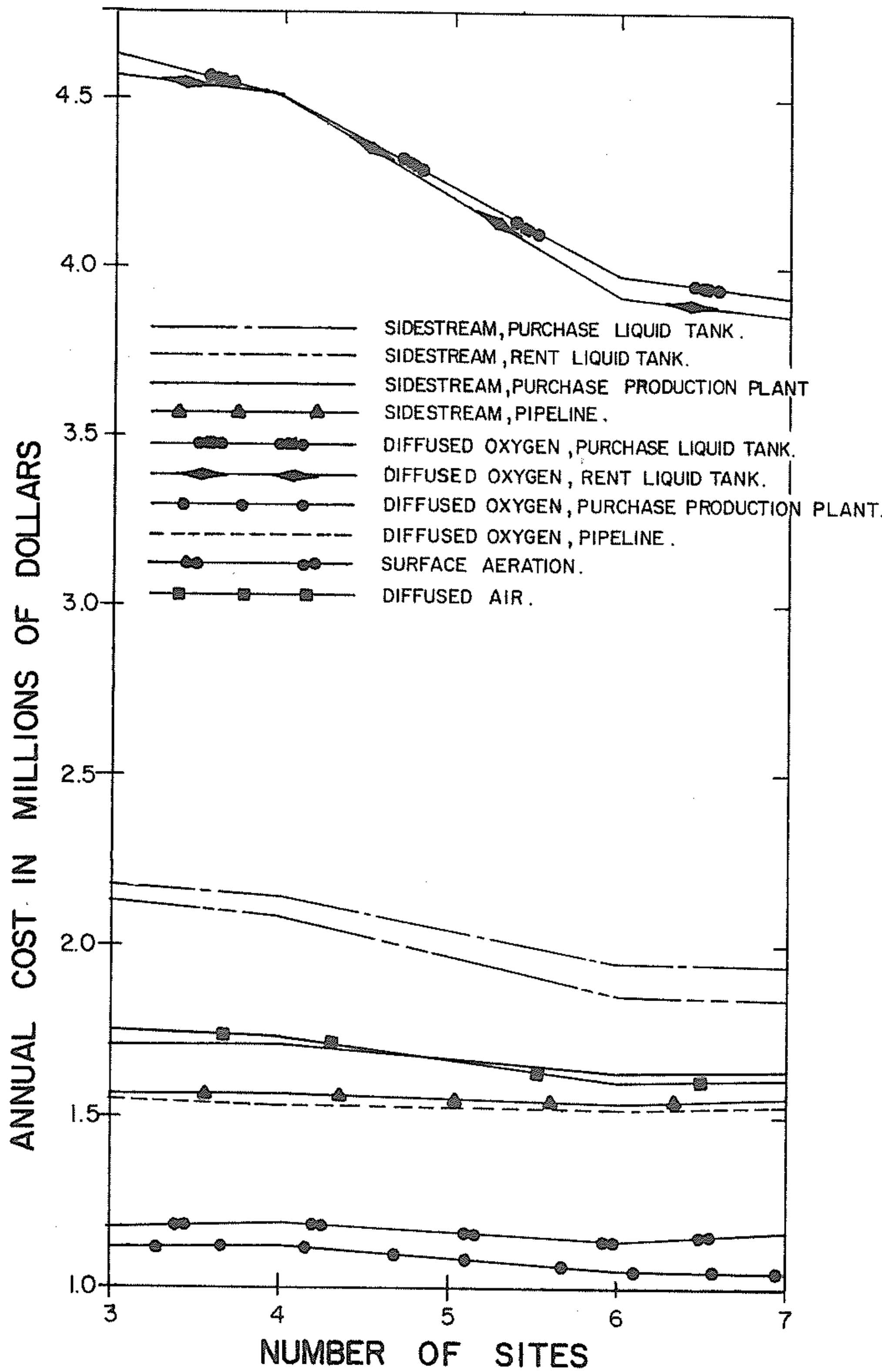

Fig. 6.9 Annual Cost of 4 mg/l Systems

alternate system can be eliminated without first evaluating the physical feasibility of each type of aeration equipment.

Physical Feasibility

The geographic and hydraulic characteristics of the channel place severe physical constraints on aeration systems making some systems infeasible and others comparatively unattractive. One of the prime constraints placed on the system selected is limited space both in the water and on shore. Maps of the seven aeration sites are given in Appendix E and they illustrate the problem. The shoreline is highly developed and access to shipping makes the available land very valuable. Space in the water, particularly in deep water, is limited by shipping operations. The channel was developed for shipping and all deepwater areas are traversed by vessels. This includes the docking areas, dredged bayous, and turning basins along the channel. Shallower water located between the bank and the dredged channel is available, but it is rarely more than 50 feet wide and the lack of depth reduces the efficiency or precludes the use of surface aeration, diffused air, and diffused oxygen equipment.

Mixing of oxygenated water with the oxygen-depleted water of the channel is necessary for efficient equipment operation and is of primary concern in the channel. The aeration site maps in Appendix E show possible usable water space on the outside of bends where the channel bank is eroded. However, these areas are shallow and dye studies indicate that they do not provide adequate transverse mixing. It is therefore difficult to locate in-channel sites suited to aeration equipment requirements.

Equipment availability is also a concern. If the equipment necessary to a particular aeration system is not available in the required size that aeration system is eliminated as an alternative.

Sidestream Oxygenation. As depicted in Fig. 2.5 (p. 10), sidestream oxygen equipment requires intake and discharge structures in the water. Pumps, oxygen supply equipment, piping, and electrical power equipment are located on shore. Because the water intake and discharge headers are submerged, a sidestream oxygenation system poses no hindrance to shipping. Collision with the intake structure is unlikely because it is only a pump wet well located at the channel's edge. Possible damage to the discharge system could occur if deep-draft vessels drag the bottom and collide with the discharge header or, if an anchor were dropped on and/or dragged across the equipment. However, damage to the discharge header can be avoided by prudent placement and the use of warning signs, such as the "no anchorage" signs currently used to protect pipelines.

The majority of the equipment necessary for sidestream aeration is land-based; therefore, land availability, particularly in the upper channel, is critical to the system. Pressure swing absorption and cryogenic oxygen plants are commonly built on 1,000 square foot plots[63] and liquid oxygen storage tanks and pipeline supply systems require less area. The pump station and control buildings will require an estimated 1,000 square feet. The contactor pipe, in order to provide the required detention time for high oxygen utilization, may be 500 or 600 feet long, but need not be straight and the configuration can be matched to the available area.

Due to a high driving force, poor mixing characteristics of the channel have minimal effect on sidestream oxygen systems. However, several features of sidestream oxygenation prevent short-circuiting. First, the water intake and discharge are sufficiently separated to allow significant dispersion of the oxygenated water between them; second, the jet action of the diffuser header and eductor nozzel discharge system maximizes initial mixing under all flow conditions; third and most important, the driving force is much less dependent on the oxygen concentration of the intake water than other systems because the high oxygen partial pressure in the transfer pipe keeps the driving force high (reference Equations 4.18 and 4.19) (p. 31, 32).

Physical desirability of oxygen supply equipment is a consideration. Storage of liquid oxygen on the site necessitates tank refilling at least every three days during peak usage and is dependent on oxygen supply trucks. Gaseous pipeline oxygen has the disadvantage of requiring right-of-way for a minimum of 7.5 miles of pipeline through valuable industrial land (land cost was not included in the cost estimates so this disadvantage does not appear in the economic comparison.) Because many of the industries in the area handle flammable petroleum products, some resistance to installation of an oxygen pipeline may be encountered. On-site oxygen production has the disadvantages associated with elaborate machinery, i.e. it requires expert operation and is subject to breakdown. During occasional shut-downs liquid oxygen stored at the site is used to continue operation, but storage tanks supplied with oxygen plants are not large and any extended shut-down requires oxygen deliveries.

A possible disadvantage to sidestream aeration are the pump requirements. To maintain system efficiency the pressure in the oxygen transfer pipe must be high (other researchers[9] have used 75 percent absorption at 100 psig). The pressure maintained determines the driving force and, therefore, the volume of water that must be pumped to carry the required amount of oxygen to the channel. To determine the feasibility of pump requirements the transfer pipe pressure is assumed to be 100 psig and the maximum oxygen injection capacity required at one site is used to calculate the necessary pump capacity. Assuming 20 psig drop along the contact pipe[61] the exit pressure will be 80 psig. Henry's Law applied to water at 80 psig gives an oxygen saturation concentration of 200 mg/1. The maximum oxygen required at any aeration site as given on Table 6.1 (p.76) is 83,000 PPD. At 200 mg/1 DO the pump capacity required to supply 83,000 PPD of oxygen is 34,556 gallons per minute (gpm). This discharge coupled with the head requirement of 100 psig can be met by available pumps.

Sidestream oxygen systems are relatively new and unproven. Design specifications have not been perfected and efficiency is highly dependent on pressure changes, eductor nozzels, and the amount of oxygen injected. The lack of design information must be considered a disadvantage to sidestream oxygenation.

<u>Diffused Aeration</u>. Figure 2.4 (p. 9) illustrates the equipment necessary to a diffused aeration system. The diffuser headers are placed in the channel and supported by pilings to maintain uniform depth. Land-based equipment includes compressors, drive motors, and electrical power equipment.

Diffusers are subject to clogging from particles in the air which escape filtration, and from suspended solids in the water when air pressure is accidentally or intentionall lost. Clogging is particularly important in the ship channel because removal and cleaning of diffusers is more cumbersome than in sewage treatment plant installations. For these reasons, the more efficient but smaller pored diffusers such as dacron socks and saran wrapping are not feasible. Wider opening spargers are necessary because of their resistance to clogging.

The poor mixing characteristics of the channel are a disadvantage to diffused air. System efficiency is dependent on the driving force and if the aerated water does not move away from the diffuser the transfer efficiency decreases.

The land-based equipment for the system requires very little space and fits in the 0.25 acres alloted per site. Minor land space requirements are an advantage in the crowded upper channel area.

Possible problems with a diffused aeration system are unreasonable blower capacities, i.e. requiring too many conventional blowers to be practical, or unreasonable diffuser header length, i.e. requiring too much piping to be practical. Table 6.4 (p. 83) illustrates the required blower capacities and the maximum at any one site is 50,900 scfm. Assuming a depth of submergence of 30 feet, neither the required capacity nor operating pressure is beyond the capabilities of readily obtainable equipment.

Diffuser lengths for a system of this size are cumbersome. Using 50,900 scfm as the required air flow and assuming 20 scfm per spargers[66] the maximum number of spargers per site is approximately 2,500. At one-foot spacing between spargers[66], the maximum required header length at one site is 2,500 feet. This length would be workable in standard sewage treatment plant conditions, but the conditions in the Houston Ship Channel complicate the problem. The headers must not extend into shipping lanes or inhibit docking operations, and they must be kept horizontal to maintain equal pressure at each diffuser. The upper channel area does not have 2,500 feet of shoreline space available for a single diffuser header so systems of laterals forming parallel diffusers will be necessary to reduce the system length; however, the channel is relatively narrow in this area and little room is available for widening the diffuser banks. The number of parallel laterals that can be used while providing access for cleaning and maintaining acceptable transfer efficiency is approximately four. With five-foot spacing between laterals, the system would extend twenty feet into the channel. In the crowded upper channel four laterals is probably the maximum number that can be fitted between shallow water and shipping lanes, and then only in selected locations. The resulting length of the header system will be 625 feet (4 laterals totaling 2,500 ft.). This length is cumbersome and will make sparger cleaning, shoreline acquisition, and header leveling difficult.

Diffused Oxygen. Several features are common to diffused oxygen, sidestream oxygenation, and diffused air systems. The advantages and disadvantages of the three oxygen supply systems are evaluated in the previous section on sidestream oxygenation and that evaluation is applicable for diffused oxygen also.

Some of the diffuser problems associated with diffused air are encountered with diffused oxygen, but the diffuser length reduction made possible by the use of oxygen lessens the difficulty. The maximum oxygen required at any one site is given as 3,730 scfm in Table 6.6 (p. 86). Assuming 20 scfm per sparger and one-foot sparger spacing the required length of diffuser header is 181 feet, a much more handleable size than the 2,500 feet calculated for diffused air. This length of header is much easier to support, keep out of the way of shipping, and clean than the air header.

The poor mixing characteristics of the channel are somewhat less a problem for diffused oxygen than for diffused air because of the high oxygen partial pressure in the rising bubbles. However, the efficiency is still highly dependent on the oxygen concentration in the water and if aerated water does not move away from the diffuser the efficiency will drop.

Surface Aeration. Surface aeration equipment is, in this paper, assumed to mean floating surface aeration. Platform-mounted surface aerators are used in sewage treatment plants but the water level variability, cost of construction, and hazard to shipping make their use for in-channel aeration infeasible.

The diagram in Fig. 2.3 (p. 8) shows a high-speed surface aerator, the most commonly used of floating aerators. Geared, or low-speed, units are available primarily in the 100 HP plus sizes. The external feasibility of the two types is the same, but there are internal differences. High-speed units are subject to bearing failure and gear units are prone to gear failure. Both units are subject to damage by rubble in the water. Because high-speed units pump water through a hole in the float, they are more likely to clog with rubble than geared units which use a large open turbine.

Surface aeration systems have minimal land-based equipment and little land area is required. The only land required is for location of electrical supply equipment and the building to house it.

Aerators are normally grouped in "banks" to facilitate anchoring and maintenance. In such banks, spacing is important to prevent short-circuiting and subsequent reduction of efficiency. The mixing zone for individual aerators varies with horsepower and a general curve illustrating this variability is derived from performance data for Aqua-Jet high speed aerators[68] and is given on Fig. 6.10. Because surface aerators transfer oxygen by increasing the water-air interface at atmospheric pressure, this system is particularly sensitive to changes in the driving force. Movement of aerated water away from the units is essential to efficient performance. To maintain acceptable oxygen transfer efficiency, the spacing between aerators in a bank cannot be less than the zone of complete mixing. The problem then becomes installing the required horsepower at a particular site without making the bank of aerators unmanageably large.

Considering the largest horsepower requirement at one site, 1729 HP from Table 6.8 (p. 91), the various unit sizes and bank configurations may be examined. As shown on Fig. 6.10 the mixing zones of common size mechanical aerators range from 75 to 175 feet. Extrapolating the curve to 200 HP indicates an approximate mixing zone of 200 feet. The maximum

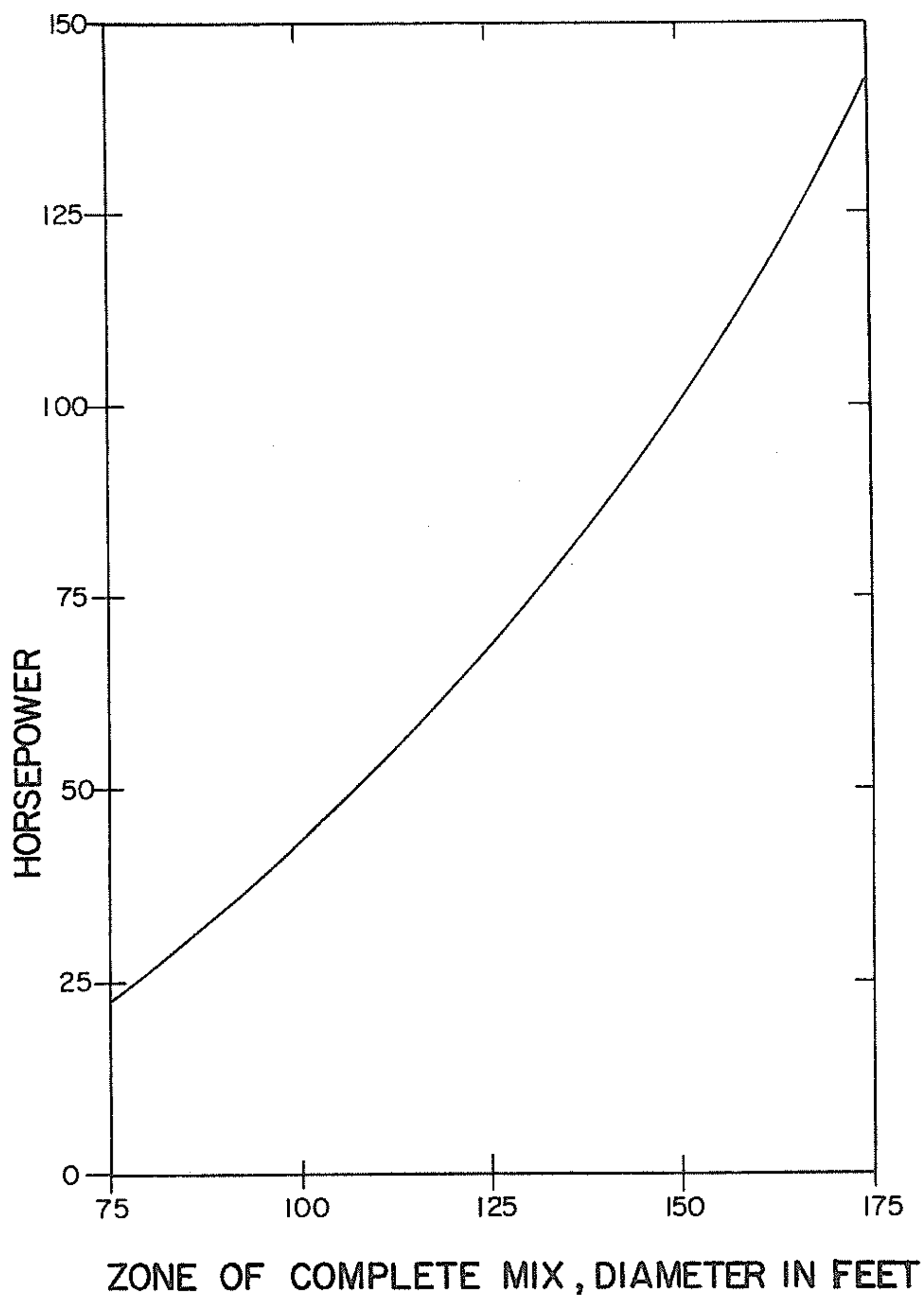

Fig. 6.10 Surface Aerator Mixing Zone

available space in the upper channel is estimated at 100 feet perpendicular to shore. Therefore, referring to Fig. 6.10 (p.104), only one row of aerators may be used. To minimize length of the aerator bank, 200 HP units may be used. The required number of 200 HP units to fulfill the power requirement is 9, making the aerator bank 1600 feet long. This length is excessive and must be reduced to make the system feasible. The spacing between units may be cut to reduce aerator bank length, but system efficiency will be reduced causing more aerators to be required.

To reduce the interference with and hazard from shipping, the banks of aerators may be located outside of the channel proper in converging bayous. Three possible locations near proposed aeration sites are Green's Bayou, Brays Bayou, and Vince Bayou. Various degrees of dredging will be required and some interference to shipping will still occur. Water movers of some type will be needed at all locations except Vince Bayou where a Houston Lighting and Power cooling water discharge probably creates adequate movement. Devices used to circulate the aerated water in this fashion will necessarily reduce the pounds per horsepower hour rating of an entire system. Extra channel locations are beyond the scope of this research and are left to future investigators.

System Selection

System selection for final design is based on economic feasibility, physical feasibility, and engineering judgement. The advantages and disadvantages of the various equipment types and site configurations are considered and two alternative systems are selected for design.

The economic analysis shows that the cost for the four equipment types with various oxygen supply equipment ranges from 0.7 to 2.9 million dollars per year for a system capable of maintaining 2 mg/l DO, and from 1.1 to 4.6 million dollars per year for a 4 mg/l system. Two systems, diffused oxygen fed by rented and purchased liquid tanks, are significantly more expensive than the other systems and are, therefore eliminated. The other systems have comparable annual cost, surface aeration being the cheapest.

The physical feasibility of the four systems is based primarily on the amount of room available in the water at or near each aerator site. On this basis in-channel surface aeration and diffused aeration must be eliminated as alternatives. Surface aeration may be feasible if aerators are located on convergent bayous out of the major shipping lanes, but elaborate water movers and hydraulic system modification will be required at most sites. The scope of this study is limited to systems operating in the channel proper; therefore surface aeration of convergent bayous is not selected as an alternative. Similarly, the large area required for air diffusers is not available in the channel and aeration of convergent channels is not considered.

The remaining alternative systems are diffused oxygen supplied by pipeline or production plant oxygen, and sidestream oxygenation supplied by any of the various oxygen supplies. Diffused oxygen requires much shorter headers than diffused air, but problems still exist. Disadvantages include loss of dock space, clogging of the diffusers, and header leveling.

Sidestream oxygenation requires minimal space in the water and only a small amount of shoreline footage for an intake structure. The equipment will not prevent docking or other ship movement and it is not prone to damage by shipping activity. The primary disadvantage of sidestream oxygenation is lack of developed design criteria. Physical desirability outweighs this disadvantage and dictates that design be undertaken so that the system may be more objectively considered. Also, the experimental nature of this study makes it acceptable to select a somewhat unproven alternative which would not be investigated in a conventional engineering study.

The oxygen supply equipment for the alternative systems can be liquid oxygen in purchased or rented storage tanks, on site oxygen production, or pipeline oxygen. Liquid oxygen is more expensive than gaseous oxygen and two site systems using this supply cost approximately $300,000 more anually than systems using other oxygen supplies. The cost of liquid oxygen systems becomes more competitive as the number of sites increases, but the disadvantages of having many sites outweigh the minor savings. Therefore, the alternative supply systems selected are pipeline oxygen and oxygen produced at the site.

System costs decrease slightly as the number of sites increases; however, land cost was not taken into account and this could be a substantial factor. Because the required water area at a site is small, there is no advantage to using a lot of sites to reduce the size of each. The disadvantages of having a system of sites widely separated outweigh the minor economic advantage. Therefore, the systems selected for design consist of 3 sites for both the 2 mg/l and 4 mg/l systems. Three is the least number of sites capable of maintaining 4 mg/l DO and selection of a 2 mg/l system with the same number of sites allows the versatility necessary to increase capacity to meet 4 mg/l criteria later.

CHAPTER VII

SYSTEM DESIGN

The two alternative systems selected in Chapter VI are both sidestream oxygen units, one supplied by pipeline oxygen and the other supplied by oxygen produced at the site. In this chapter preliminary designs are made for the two alternative systems with capacities capable of maintaining both 2 mg/l and 4 mg/l DO in the Ship Channel. The basic layout of a sidestream oxygenation system is shown in Fig. 2.4(p. 9) and a more detailed drawing is given in Fig. 7.1. The primary components of the system are listed below:

1. Oxygen Source
2. Pump Station
3. Pipeline Contactor
4. Pressure Control Value
5. Distributor Header

Modeling done in Chapter V determined the oxygen required at each site to maintain criteria DO and the site configuration was selected in Chapter VI. The findings are summarized below:

Site Location (1/4 mile segments)	Required Oxygen Transfer 2 mg/l	4 mg/l
1	30,000 PPD	60,000 PPD
17	56,000 PPD	60,000 PPD
29	18,000 PPD	60,000 PPD

Sidesteam oxygenation is a recently developed aeration system and design parameters which are well known for other equipment are either unknown or unproven for this system. Linde Division of Union Carbide markets the Lindox sidestream oxygen system and Olszewski has experimented with this equipment in both bench and

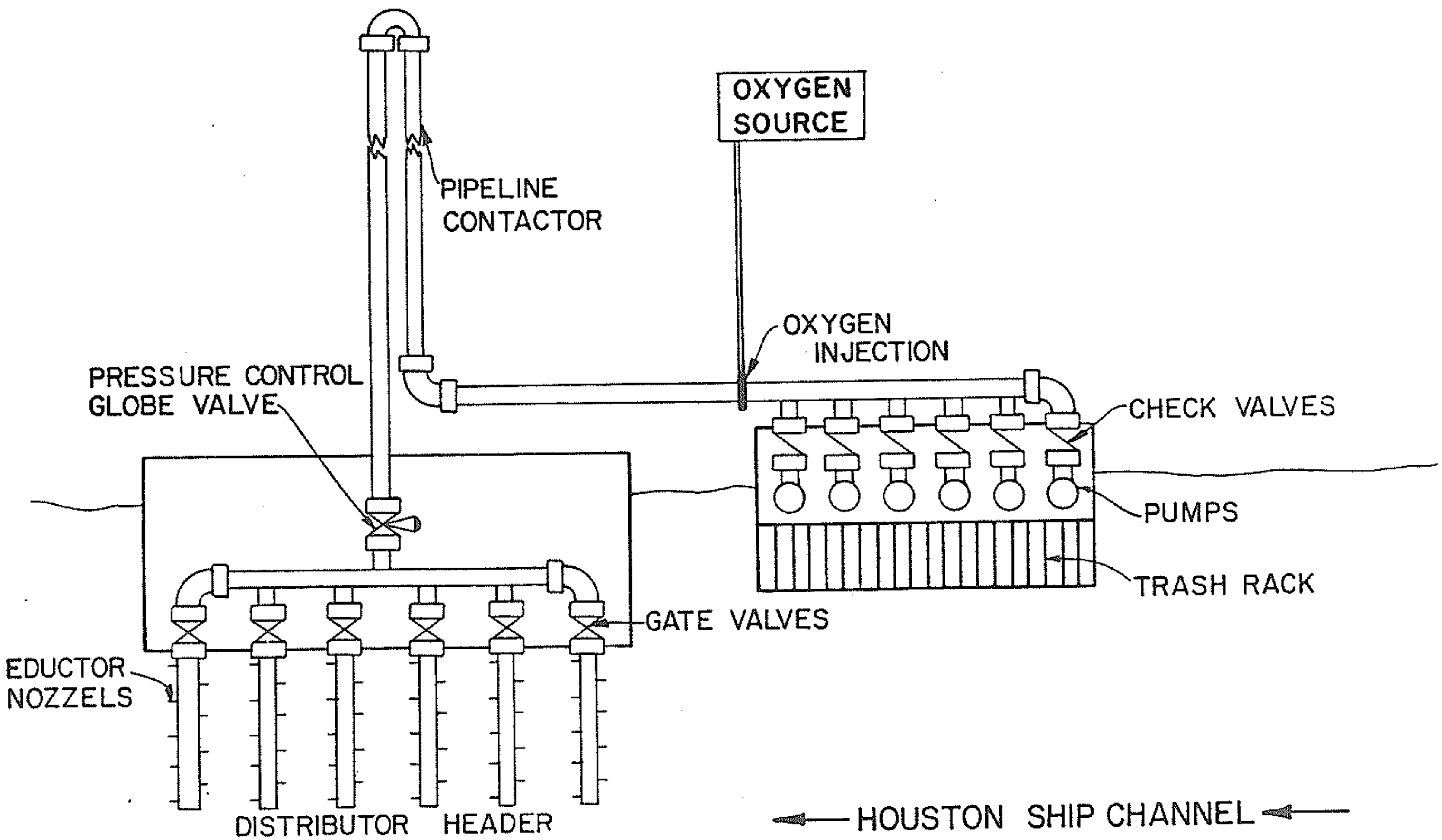

Fig. 7.1 Detailed Drawing of Sidestream Oxygenation System

pilot scale studies. His work provides much useful information[61,69], but there are data gaps and the available data are often uncorroborated. With these conditions, a state of the art preliminary design is developed.

Pipeline Contactor

The efficiency of oxygen transfer in the pipeline contactor (Fig. 7.2) dictates the size of the system components. The design considerations which affect the transfer are inlet and discharge pressure, energy loss through the pipe, detention time, amount of oxygen injected, and the coefficient of mass transfer.

The change in oxygen concentration with time was discussed in Chapter IV and equation 4.17 (p.31) was derived to describe oxygen transfer. Convention in artificial aeration names the coefficient K_La instead of K_a, but equation 7.1 below is otherwise the same as equation 4.17 (p. 31).

$$\frac{dc}{dt} = K_La(C_s - C) \qquad (7.1)$$

where

t = time
C = concentration at t
C_s = saturation concentration
K_La = overall oxygen transfer coefficient specific to the system

The values of K_La and C_s are independent of time so equation 7.1 integrates to:

$$- K_La\ (t) = \ln\left(\frac{C_s - C_{discharge}}{C_s - C_{intake}}\right) \qquad (7.2)$$

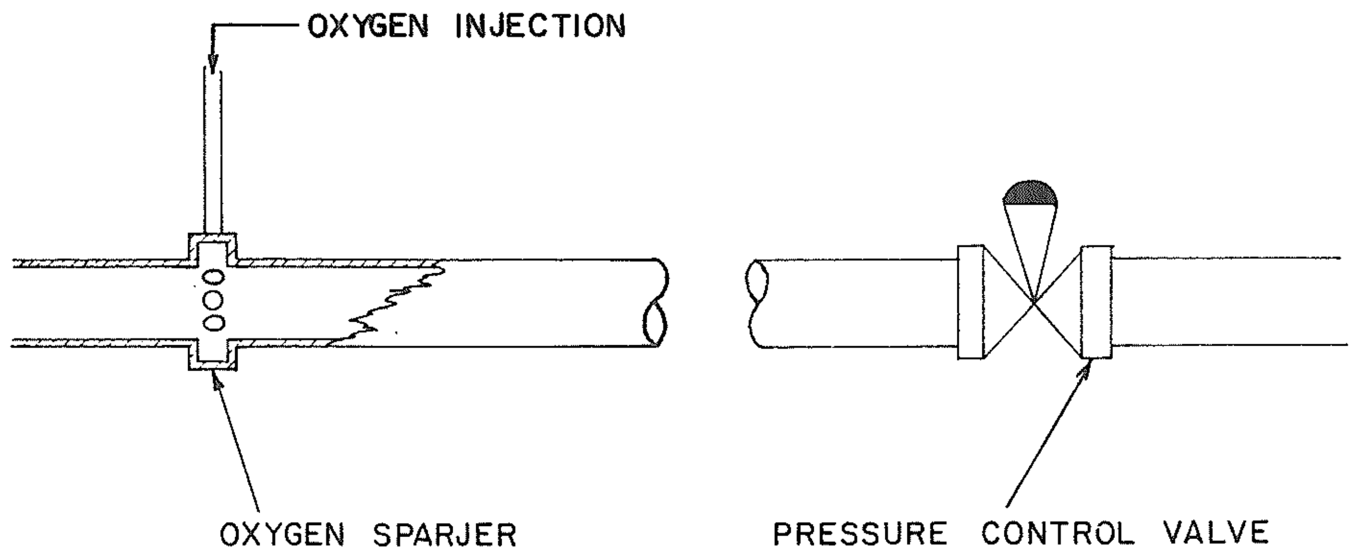

Fig. 7.2 Oxygen Pipeline Contactor

where

C_{intake} = concentration in the channel
$C_{discharge}$ = concentration at the contactor exit

The coefficient K_La includes several very difficult to obtain terms such as gas/liquid interfacial area and hypothetical liquid film thickness, so K_La for aeration systems is determined experimentally. Olszewski[61] has investigated K_La values and his data are plotted on Fig. 7.3. The slope of the eight lines shown represents the K_La values under different test conditions. Four tests were run at different system pressure drops (5, 10, 15, and 20 psig) and oxygen supplied in an amount equal to 100 percent of the oxygen was required to saturate the discharge water. Another four tests were run with the same pressure drops, but only 75 percent of the oxygen was required to saturate. Olszewski chose target $C_{discharge}$ values of 50 percent of saturation and 70 percent of saturation, causing the experimental data to fall on two horizontal lines. The result is, even though some points are duplicated, no line is defined by more than two points. This in itself is disconcerting, but the problem is compounded by the fact that none of the lines pass through 1.0 on the ordinate as they must for K_La to be independent of time and for the derivation of equation 7.2 (p.111) to be correct. Despite this discrepancy in the data, the K_La values determined are considered valid for the range of tested conditions and, in the absence of more extensive testing, are used for design.

Olszewski selected 50 percent saturation and 70 percent saturation as $C_{discharge}$ values because his previous experimentation indicated

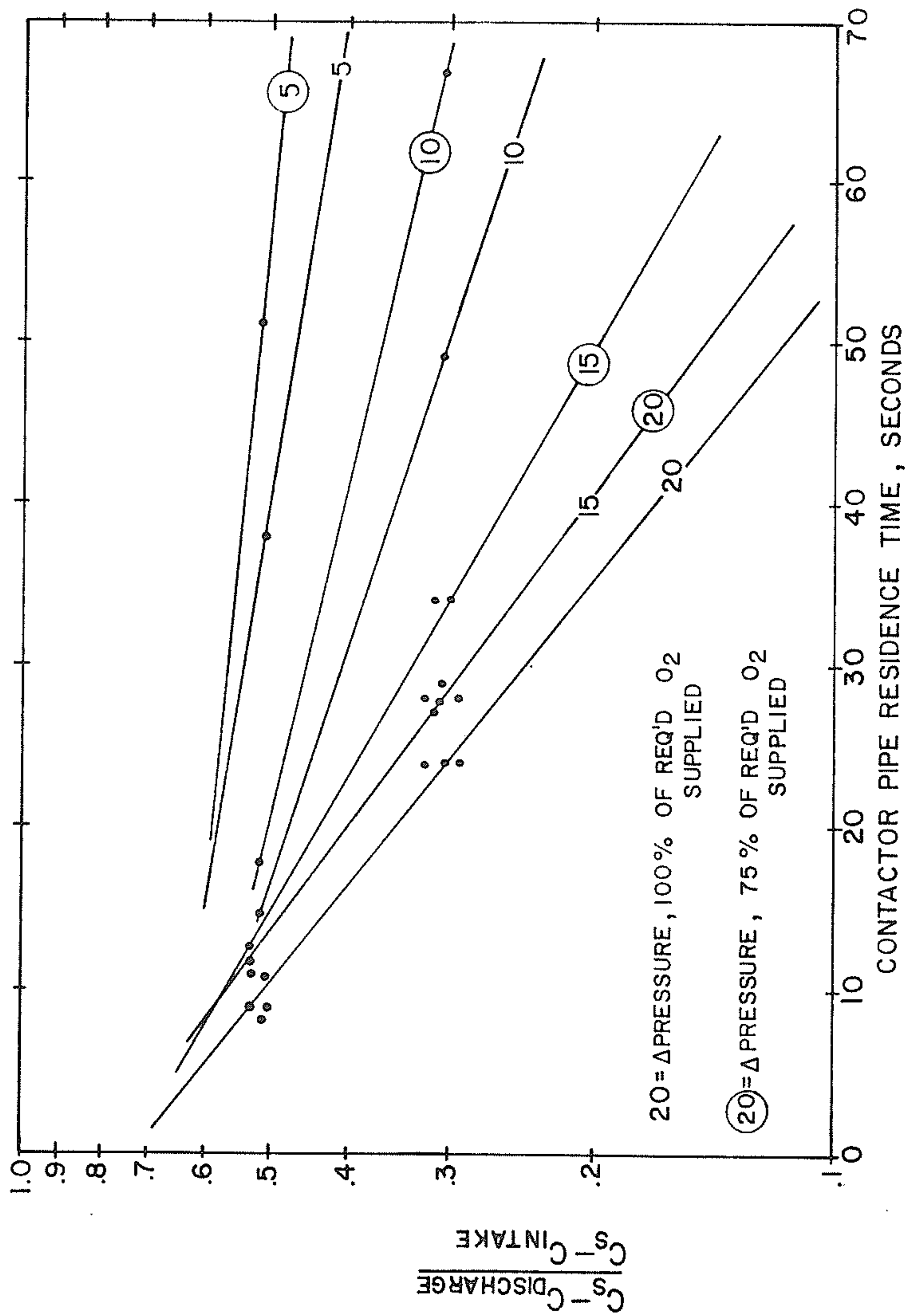

Fig. 7.3 K_La Values for Sidestream Oxygenation System

degassing problems in the distributor header at higher concentrations.[61] Field and lab tests show that 50 percent saturated water could be distributed without detrimental degassing if the length of the distributor pipe were kept as short as possible. By fitting the discharge ports with eductor nozzels, which more quickly mix the oxygenated water with the stream, 70 percent saturated water could be distributed without detrimental degassing.

Having achieved 50 percent and 70 percent saturation values for $C_{discharge}$ while sparging 100 percent of the required oxygen, Olszewski dropped the mass of sparged oxygen to 75 percent of the amount required to saturate. As seen on Fig. 7.3 (p.114) at a pressure drop of 20 psig only a slight decrease in slope occurred when the sparged oxygen was decreased 25 percent. The oxygen absorption efficiency changed from 70 percent (0.70 absorbed/1.00 sparged) to 90 percent (0.70 absorbed/0.75 spar ed). The substantial oxygen savings experienced by sparging only 75 percent of the oxygen required to saturate outweigh the minimal increase in K_La.

The inlet pressure is critical to performance of the contactor because it determines the saturation concentrations and, therefore, the driving force in the pipe. Equation 7.1 (p.111) indicates that the greater the inlet pressure the greater the oxygen transfer, however, problems develop over 100 psig. Olszewski[61] cites the following reasons for limiting the inlet pressure to 100 psig: expense of water pumps, pipes, and fittings; difficulty in obtaining compressors to boost the oxygen pressure; and the necessity to dissipate pressure in the distributor prior to discharge without degassing. For these reasons 100 psig inlet pressure is used herein.

As seen in Fig. 7.3(p.114), K_La increases significantly as the pressure drop increases from 5 to 20 psig. The increased liquid shear forces produced by the turbulent flow keep the oxygen bubbles small and well mixed, thereby increasing the gas/liquid interfacial area and the value of K_La. As the pressure drop increases for a given inlet pressure, C_s at the outlet drops, acting to offset the K_La increase realized from the pressure drop. Using Olszewski's data for straight pipes and incremental pressure drops from 5 to 25 psig and inlet pressure equal to 100 psig, the graph on Fig. 7.4 is plotted. As the plotted line illustrates at $\Delta P = 20$ psig the decrease in C_s at the discharge offsets the increased K_La and dc/dt levels off. Therefore, the optimum pressure drop for an inlet pressure of 100 psig is 20 psig.

The increase in K_La due to the shear forces created by turbulent flow suggests that artificial mixers placed in the contactor or use of a curved contactor pipe might improve efficiency. However, Olszewski[61] concludes that for a fixed total pressure drop the loss of contact time, t, resulting from the use of artificial mixers or pipe loops is of a greater magnitude than the resulting increase in K_La and, as can be seen from equation 7.2 (p.111), the contactor thus produced will not be as efficient as a straight pipe.

The possibility of excessive corrosion exists when high concentrations of oxygen in water are involved and the material that the contactor is made of must be sufficiently resistant. Olszewski[61] found no problems with schedule 40 carbon steel pipe and he recommends its use. This pipe is readily available in standard diameters.

In summary, the contactor design parameters selected from an analysis of Olszewski's data and recommendations are: inlet pressure equal to 100 psig, pressure drop equal to 20 psig, $C_{discharge}$ equal to 0.70 C_s, construction with schedule 40 carbon steel pipe, and oxygen supply equal to 75 percent of the amount required to saturate at exit conditions. Given these parameters the value of K_La from Fig. 7.2 (p.112) is 0.04 sec $^{-1}$. Designing for these conditions produces a specific pipe size which will most likely not be a standard size. Therefore, preliminary calculations are made to determine the ideal pipe size, the nearest standard size is selected, and the design parameters commensurate with the standard pipe size are calculated.

The oxygen saturation concentration (C_s) at 80 psig and 20^o C is 286 mg/1, making C equal to 200 mg/1 ($C = 0.70C_s$). At this concentration the discharges are calculated and given in Table 7.1. Using Equation 7.2 (p.111) and the given design parameters the detention time, t, is calculated as follows:

TABLE 7.1

Preliminary Contactor Design

Site Location (¼ mile segment)	Required Oxygen Transfer (PPD)		Discharge Volume $C_{discharge}$=200mg/l (cfs)		Contactor Volume (ft^3)		Pipe Diameter (in.)		Pipe Length (ft)	
	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l
1	30,000	60,000	27.8	55.6	834	1668	15.68	20.91	621.9	699
17	56,000	60,000	51.9	55.6	1557	1668	20.32	20.91	691.4	699
29	18,000	60,000	16.7	55.6	501	1668	12.69	20.91	570.4	699

$$-K_L a(t) = \ln \left(\frac{C_s - C_{discharge}}{C_s - C_{intake}}\right)$$

$$\frac{-\ 0.04\ t}{sec} = \ln \left(\frac{286-200}{286-\text{Criteria}}\right)$$

$$t = \quad sec$$

Because C_s is large relative to C_{intake} the criteria value used (2 mg/l or 4 mg/l) has little effect on t. The detention time and discharges are used to calculate the contactor volumes shown in Table 7.1 (p. 118).

To get the proper range for the contactor diameter and length, the Hazen-Williams formula is used. Written for head loss the equation is[70] :

$$h_f = \frac{4.727}{D^{4.87}}\ L \left(\frac{Q}{C_1}\right)^{1.85} \tag{7.3}$$

where

h_f = head loss in feet of water
D = inside pipe diameter in feet
L = pipe length in feet
Q = discharge in cfs
C_1 = surface roughness coefficient (130 for schedule 40 steel pipe)

The volume of the contactor pipe is given by:

$$V = L \left(\frac{\pi D^2}{4}\right) \tag{7.4}$$

Combining equations 7.3 and 7.4 yields:

$$D = \sqrt[6.87]{\frac{18.9V}{\pi h_f}\left(\frac{Q}{C}\right)^{1.85}} \tag{7.5}$$

Solving equation 7.5 for pipe diameter and using equation 7.4 to determine pipe length gives the dimensions shown in Table 7.1 (p.118).

Assuming the contactor configurations shown in Fig. 7.1 (p.110), the contactors will consist primarily of two lengths of straight pipe 300 to 400 feet long and a 180° return bend. A shorter length of pipe and a 90° bend will lead from the pump station to the contactor. It is desirable to keep the equipment on as small a site as possible and more bends could be used to reduce the pipe length to any size, but the accompanying pressure drop must be avoided if possible. A review of the site locations (Appendix E) indicates that 400 feet of land in a narrow line perpendicular to the channel is probably obtainable and the contactor can be constructed with only one bend as shown in Fig. 7.1 (p.110).

A problem arises in that the pipe diameters given in Table 7.1 (p.116) are not standard pipe sizes and would be very expensive if a special order were made. Using the Hydraulics Institute Pipe Friction Manual,[71] standard size schedule 40 steel pipe diameters near those calculated are selected and listed in Table 7.2. All of the design parameters are related to the pipe diameter and the change to standard pipe size necessitates redesign of the contactor. A trial and error approach is used to arrive at the optimal balance between the interrelated design parameters.

The Pipe Friction Manual[71] gives head loss for straight pipes and bends and these are shown on Table 7.2 for the listed pipe size. The contactor length necessary for t = 30 seconds is given on Table 7.2 and used to calculate the pressure drop through the contactor. Four of the six pressure drops calculated are greater than 30 psig and are out of the experimental range used

TABLE 7.2

Contactor Pipe Design

Site Location (1/4 mile segment)	Standard Pipe Diameter ("OD/"ID)		Pipe Head Loss (ft/100ft)		Bend Head Loss (ft)		Contactor Length Required for t = 30 sec (ft)		Pressure Drop (psig)		K_La (sec^{-1})		C_s (mg/l)		$C_{discharge}$ (mg/l)		Discharge (Q) (cfs)	
	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l	2mg/l	4mg/l
1	16/15.00	20/18.81	8.31	10.20	0.82	1.29	679.6	864.4	24.90	38.89	.04	.05	268	226	188	176	29.6	63.2
17	20/18.81	20/18.81	8.87	10.20	1.10	1.29	806.3	864.4	31.56	38.89	.05	.05	248	226	193	176	53.8	63.2
29	12/11.94	20/18.81	9.88	10.20	0.72	1.29	641.1	684.4	27.77	38.89	.04	.05	259	226	181	176	18.5	63.2
							t = 40 sec											
1	18/16.88	24/22.62	4.57	3.97	0.50	0.48	715.5	800.0	14.39	14.0	.03	.03	299	300	209	210	26.6	53.0
17	24/22.64	24/22.62	3.47	3.97	0.45	0.48	744.1	800.0	11.40	14.0	.02	.03	308	300	170	210	61.1	53.0
29	14/13.12	24/27.62	6.09	3.97	0.55	0.48	711.5	800.0	19.10	14.0	.04	.03	285	300	228	210	14.6	53.0

by Olszewski. Figure 7.4 indicates that these pressure drops are well out of the optimal range for oxygen transfer and commensurate K_La values can only be estimated. However, the values are estimated and the calculations continued on the table for purposes of comparison. The saturation values for 20^oC and the contactor exit pressures (assuming 100 psig inlet pressure and the calculated pressure drops) are calculated and listed on the table. Using equation 7.2 (p.111), the contactor discharge concentration is calculated and used to find the discharge flow required to supply the needed oxygen, both $C_{discharge}$ and Q are given in Table 7.2 (p.121).

The discharge volumes for the four contactors with pressure drops outside the range of the experimental data (site 17 at 2 mg/l criteria and all 3 sites at 4 mg/l criteria) are higher than those predicted with the Hazen-Williams formula and given on Table 7.1 (p.118); therefore, the head loss is significantly greater than that taken from the Pipe Friction Manual and given on Table 7.2 (p.121). In turn, the higher head losses extend the K_La estimates further from experimental data and reduce C_s further. In short, if the discharge given on Table 7.2 (p. 121)is significantly larger than the estimated discharge used to calculate it, a recalculation is necessary and the resulting discharge will be bigger still.

To escape this looping effect and bring the pressure drops into the range of Olszewski's experimental results, larger standard pipe sizes are selected and the process is repeated. The values for the second selected pipe size are given on the bottom of Table 7.2 (p.121). As noted on the table, the detention time was increased

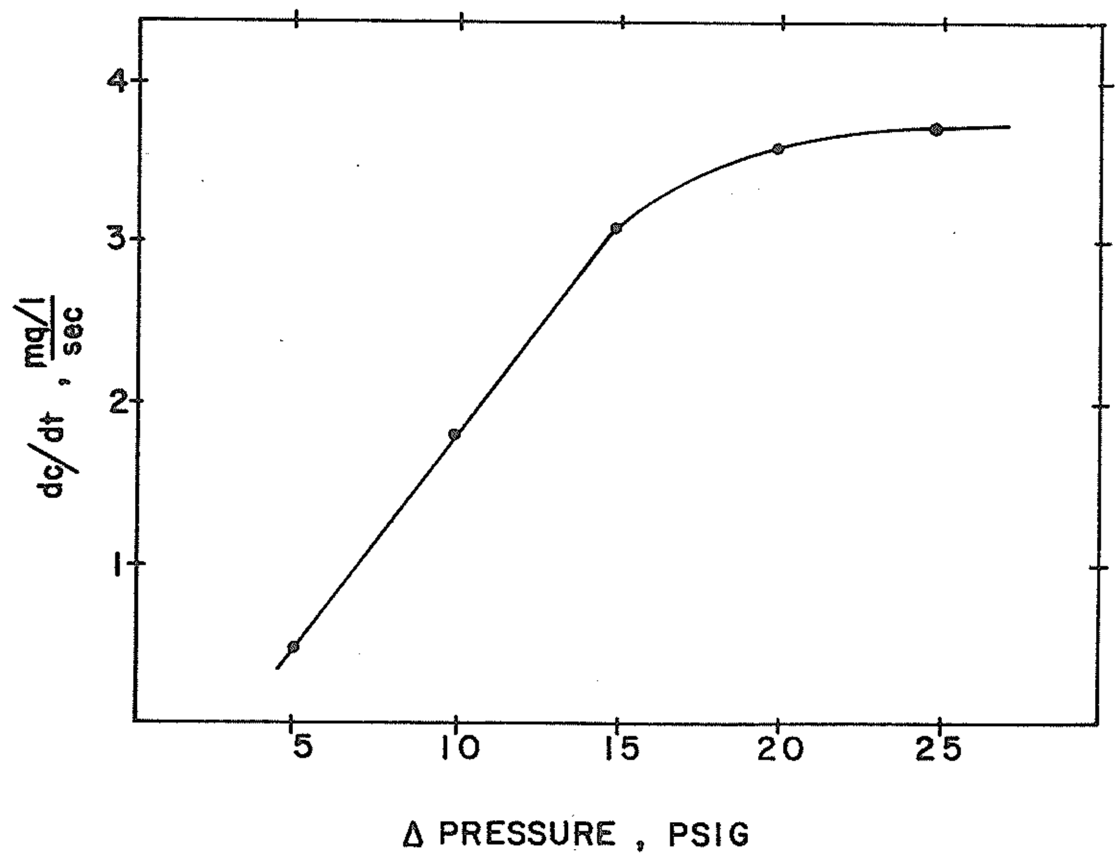

Fig. 7.4 Oxygen Transfer vs. Pressure Drop

to 40 seconds to compensate for the decrease in K_La values.

Also recalculated and shown on the bottom of Table 7.2 (p.121) are the values for the contactor at segment 1 for 2 mg/l criteria. The pressure drop for this contactor was in the experimental range in the first trial, but one larger size pipe is investigated for comparison.

The selected contactor dimensions and recalculated design parameters are given on Table 7.3. The discharges used to begin the calculation are those reported on Table 7.2 (p.121). The actual oxygen transfer is calculated and compared to the oxygen required at the right of Table 7.3.

Pressure Control Valve

The pressure control valve located at the discharge end of the contactor pipe is used to maintain pressure in the contactor and dissipate energy, reducing the pressure to 20 to 30 psig for discharge. The valve provides a means of fine-tuning the system for maximum oxygen transfer under varying discharges. Until more is known about the operation of sidestream oxygenation systems in general, and these units in particular, automatic control valves are not used. Hand operated globe valves are well suited to control application and are specified here. Globe valves are readily available in the sizes required and the valve seats resist erosion when the valves are operated partially closed.

Pump Station

The pump stations must produce relatively high discharges against 100 psig (230 ft. H_2O) of head for the contactors to operate

TABLE 7.3

Contactor Pipe Design Check

Site Location (1/4 mile segment)	Discharge (cfs)		Standard Pipe Diameter ("OD/"ID)		Pipe Head Loss (ft/100 ft)		Bend Head Loss (ft)		Detention Time, t (sec)		Contactor Length (ft)		Pressure Drop (psig)		K_La (sec^{-1})		C_s (mg/l)		$C_{discharge}$ (mg/l)		Oxygen Transferred (PPD)		Oxygen Required (PPD)	
	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l	2 mg/l	4 mg/l
1	26.6	53.0	18/16.88	24/22.62	4.19	3.61	0.46	0.56	40	40	685	760	12.6	12.2	.03	.03	304	305	213	214	30546*	61149*	30000	60000
17	61.1	53.0	24/22.62	24/22.62	4.77	3.61	0.75	0.56	40	40	876	760	18.5	12.2	.04	.03	289	305	229	214	15435	61149*	56000	60000
29	14.6	53.0	14/13.12	24/22.62	4.70	3.61	0.37	0.56	40	40	622	760	12.9	12.2	.03	.03	303	305	212	214	16687	61149*	18000	60000
1																								
17	53.5		24/22.62		3.67		0.57		40		767		12.5		.03		305		194		55822*		56000	
29	15.6		14/13.12		5.32		0.43		40		665		15.6		.035		295		223		18734*		18000	

* VALUES SELECTED

properly. Also, the system must have adequate variability to allow discharge reduction when less than the maximum amount of oxygen is required. The discharge requirements for the pump stations vary from 7,000 to 24,000 gallons per minute (gpm) as shown on Table 7.4. These large discharge values and the presence of particulate matter in the water make positive displacement pumps impractical. Centrifugal pumps can supply the required discharge and pass substantial particulates without damage, but slippage prevents most individual centrifugal pumps from producing the required head. However, centrifugal pumps can be assembled in series on one drive shaft and each stage increases the discharge head. Fig. 7.5 illustrates a pump station with mixed flow stage pumps, a wet well, and a collection header pipe.

To provide system variability, several stage pumps are provided at each pump station. Swing type check valves between the pump discharges and the contactor allow any of the pumps to be shut down to conserve energy or for maintenance without shutting the system down.

The total dynamic head requirements for each pump include, in addition to 130 feet in the contactor, the friction losses through a vertical pipe, a 90 degree coupling, a check valve, and, if needed, a transition from the check valve to the contactor. However, the friction losses through the fittings are insignificant compared to 230 feet of H_2O and pump curves are not precise enough to make calculating these losses necessary. Pump selection is made on the basis of 230 feet of head and the discharges listed on Table 7.4.

TABLE 7.4

Pump Specifications

Site Location (1/4 mile segment)	Total Discharge at 230 ft. Head (G.P.M.)		Number of Pumps		Discharge Per Pump (G.P.M.)		Head Per Stage (ft)		Storage Required for 230 ft. of head		Horsepower Required Per Stage		Efficiency %	
	2mg/1	4mg/1	2mg/1	4mg/1	2mg/1	4mg/1	2mg/1	4mg/1	2mg/1	4mg/1	2mg/1	4mg/1	2mg/1	4mg/1
1	11939	23788	3	6	3980	3965	58	58	4	4	70	70	86	86
17	24013	23788	6	6	4002	3965	58	58	4	4	70	70	86	86
29	7002	23788	2	6	3501	3965	58	58	4	4	56	70	86	86

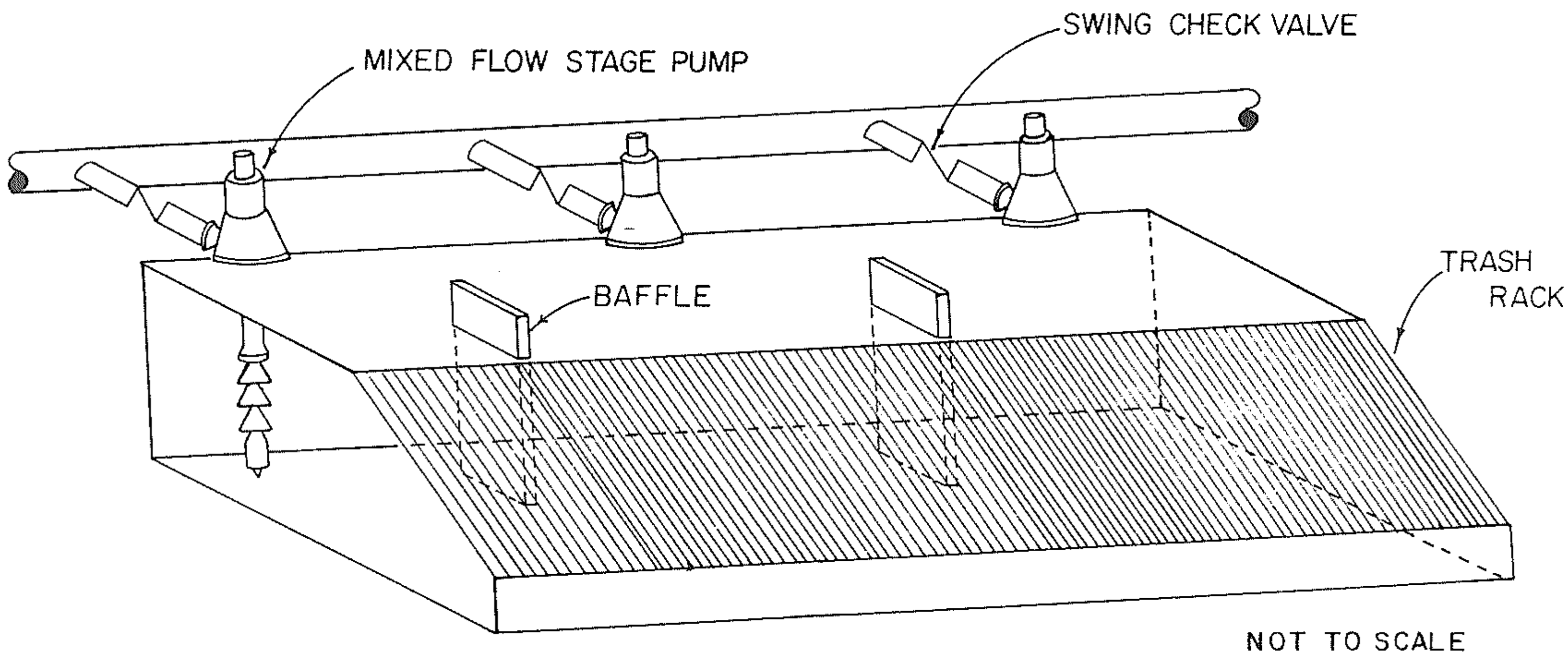

Fig. 7.5 Pump Station

Pump selection is based on variability and cost. A few large pumps represent less capital and operating cost than many small pumps, but less discharge variability is provided. Typical pump curves are shown in Figs. 7.6 and 7.7. The pump specifications on Table 7.4 (p.125) are taken from them.

Electric drive motors are mounted vertically above the pumps. The horsepower required per stage shown on the pump curves increases as the head decreases and the discharge increases. The result in the present application is more required horsepower if the pressure regulation valve is opened and the head reduced. To avoid damage to the motors under these conditions the maximum horsepower requirements shown on the pump curves are specified. The horsepower required per pump and the horsepower of the nearest available motor size is given on Table 7.5. Specifications for the horsepower and RPM shown are for 3 phase--60HZ, 2300volt squirrel cage induction motors.

The pump head or coupling is a right angle pipe bend with a motor mount and drive shaft port on top. A variety of sizes and types of heads are available from pump manufacturers and selecting one to fit the motor and contactor pipe is no problem; therefore, a transition between the pump and the contactor is not needed.

A swing type check valve is used at each pump discharge to prevent backflow if the pump is intentionally or accidentally shut down. These valves are easily obtainable in the same diameters as the discharge pipes.

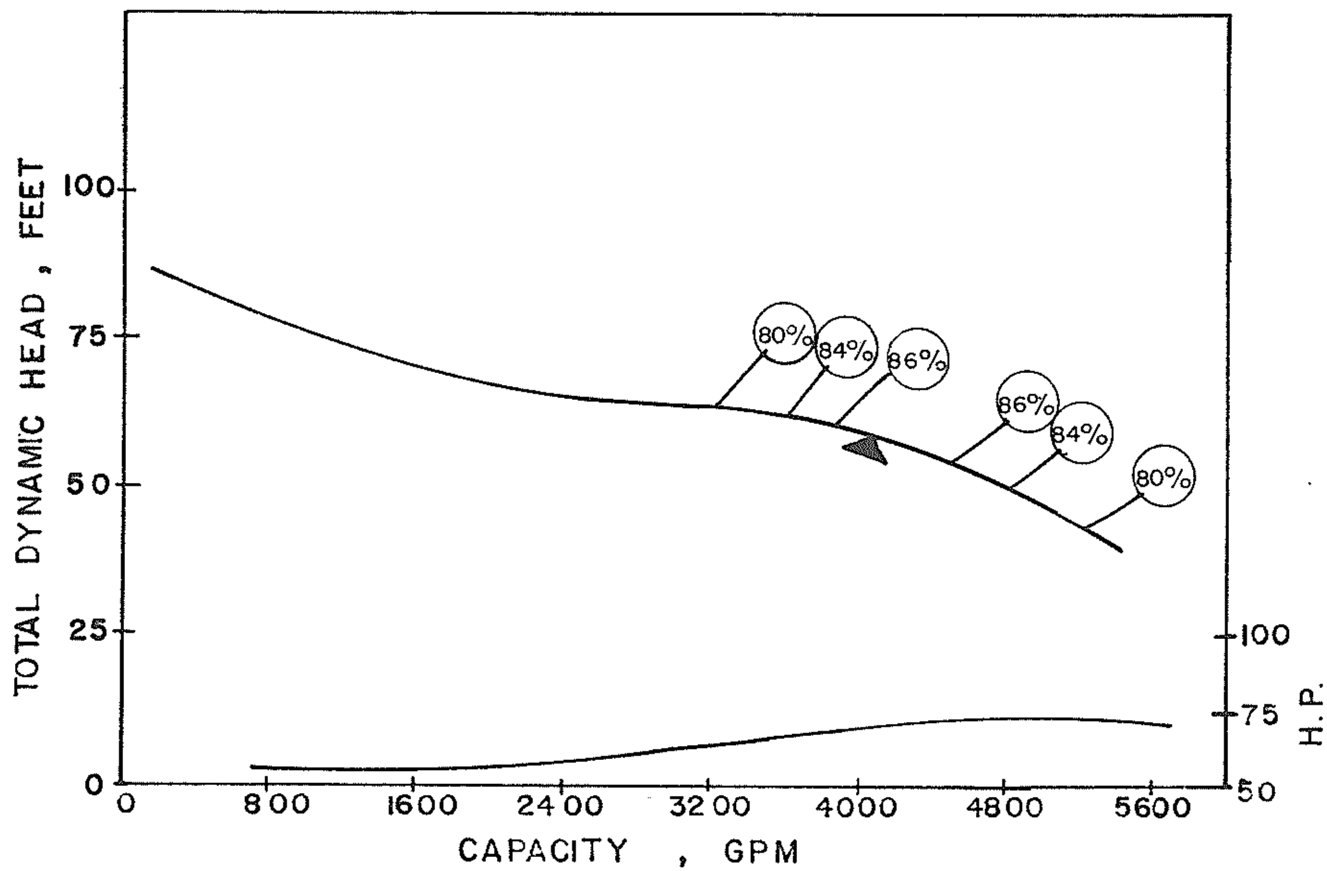

Fig. 7.6 1st Typical Pump Curve

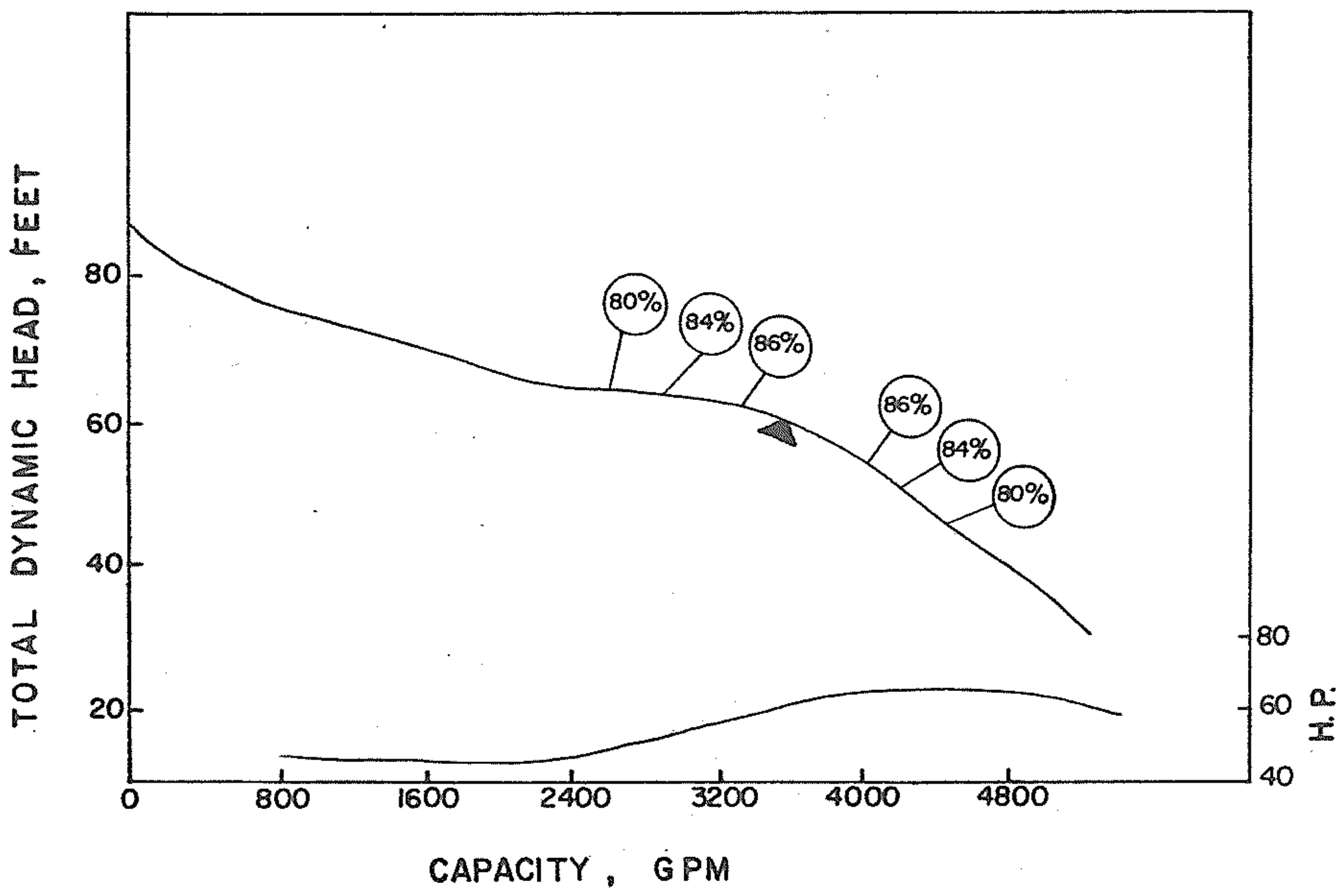

Fig. 7.7 2nd Typical Pump Curve

TABLE 7.5

Drive Motor Specifications

Site Location (1/4 mile segment)	Maximum HP per Stage		HP per Pump		HP/RPM Selected*	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	75	75	300	300	350/1200	350/1200
17	75	75	300	300	350/1200	350/1200
29	64	75	256	300	300/1200	350/1200

*3 Phase - 60 HZ, 2300 volts

The pump station wet wells or sumps must supply an evenly distributed flow to each pump bell. They are concrete structures constructed at considerable expense inside a temporary sheet pile dam on the edge of the channel. The pumps specified will pass a one-inch diameter sphere so a trash rack with one-inch spacing is provided. Automatic cleaning for the trash rack is not provided. Fig. 7.8 shows a generalized wet well with the required dimensions.[72] The concrete walls are one foot thick, the slab is 1.5 foot thick, and the top is 0.5 foot thick.

Distributor Design

To prevent degassing the distributor must have a low detention time and mix the oxygen-rich water with the channel water quickly. Other requirements are accessibility for maintenance and the ability to handle variable discharges.

The low detention time requirement must be somewhat compromised in order to provide system variability and accessibility. The distributor header configuration providing the lowest detention time uses as little out of the water piping as possible so that the nozz e to header length ratio may be maximized. However, accessibility and adequate velocity through each nozzle under varying discharges is hard to achieve with such a system. The distributor shown in Fig. 7.9 allows each header to be removed from the water for inspection and maintenance. When channel conditions allow operation at less than maximum discharge unused headers are shut off with the valves provided, thereby maintaining pressure at the nozzles in use.

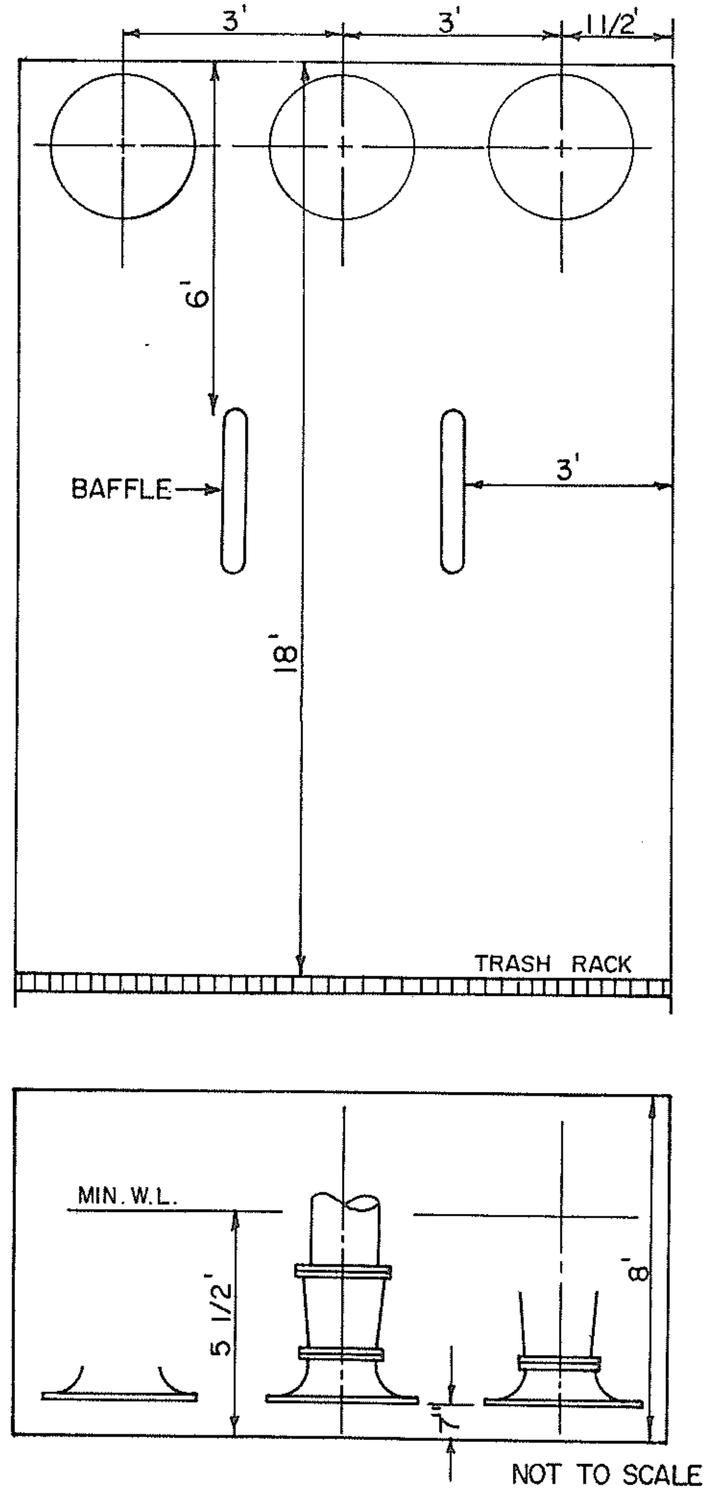

Fig. 7.8 Wet Well Dimensions

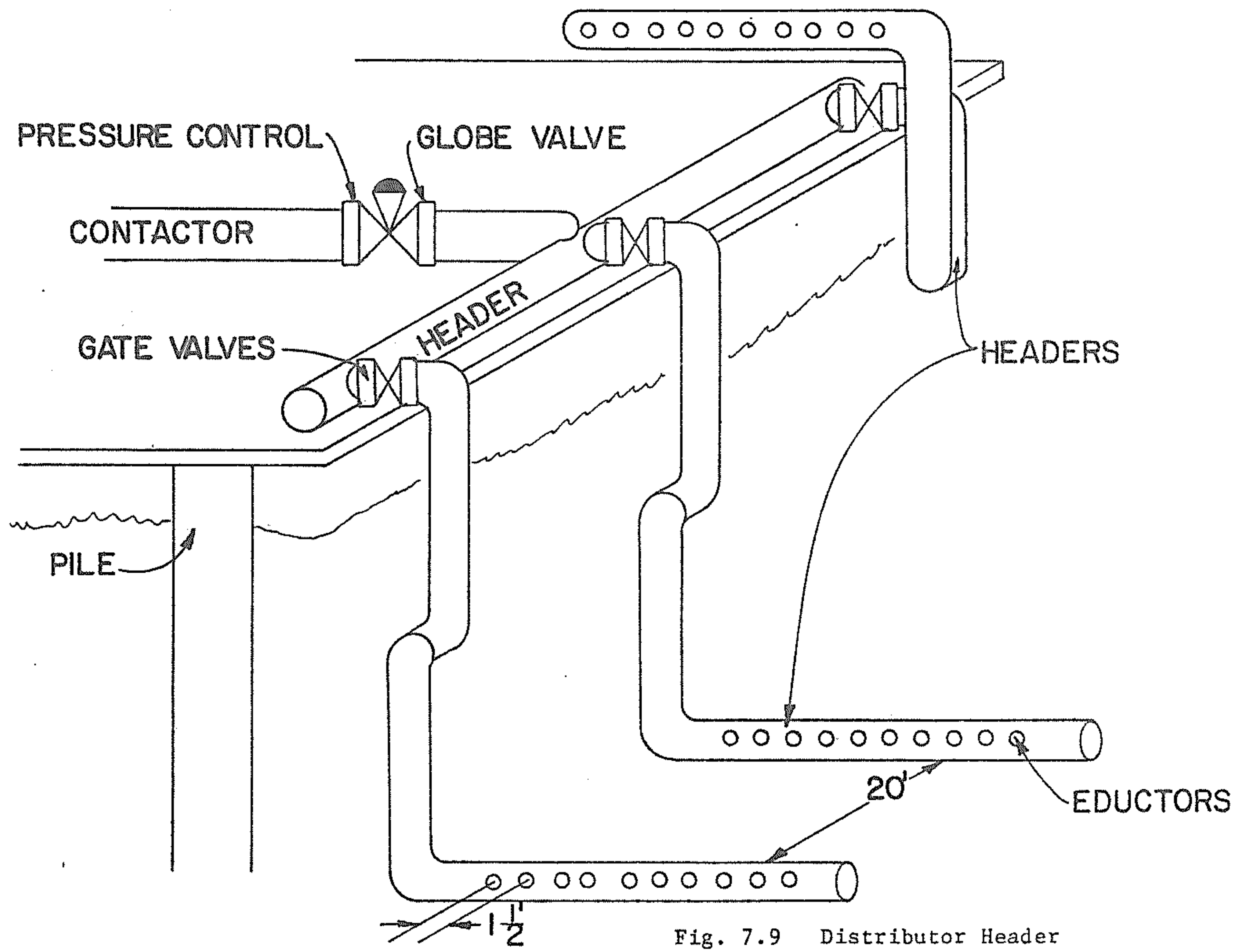

Fig. 7.9 Distributor Header

One header is used for each pump at a site. When a pump is shut down one header is shut off, thereby maintaining adequate pressure for mixing at each of the discharge nozzles. The discharge through each header is equal to the discharge from one pump. The most economical pipe sizes are used for the headers [73] and the values are given in Table 7.6. The procedure of using one header for each pump facilitates increasing system capacity from a 2 to a 4 mg/l system.

The required mixing is accomplished with eductor nozzles which entrain channel water into the discharged water before it leaves the nozzle (Fig. 7.10). Three-inch Penberthy eductor nozzels have a flow of 210 gpm at 20 psig.[61] The required number of eductors of this capacity for each header is given in Table 7.6. The eductor nozzles are spaced 1.5 feet apart and directed at a 45 degree angle from the bottom on alternate sides of the distributor headers. Using this spacing the required header lengths are given on Table 7.6. The difference in head between the entrance and end of each discharge header must be small in order to have even flow through each nozzle. The head losses through the laterals are calculated in Appendix F and found to be less than 1.0 psig; therefore, flow through the nozzles will be virtually equal.

Oxygen Supply Equipment

Oxygen is either supplied by an air reduction plant located at each site or by an extension of an existing oxygen pipeline. In the preliminary analysis oxygen utilization was estimated conservatively at 75 percent, but more thorough design has shown

TABLE 7.6

Distributor Specifications

Site Location (1/4 mile segment)	Number of Distributor Headers Required		Header Pipe Diameter (in.)		Lateral Pipe Diameter (in.)		Required Number of 3" Eductors per Header		Distributor Header Length (ft)	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	3	6	14	24	14	14	19	19	29.0	29.0
17	6	6	24	24	14	14	19	19	29.0	29.0
29	2	6	12	24	12	14	17	19	26.0	29.0

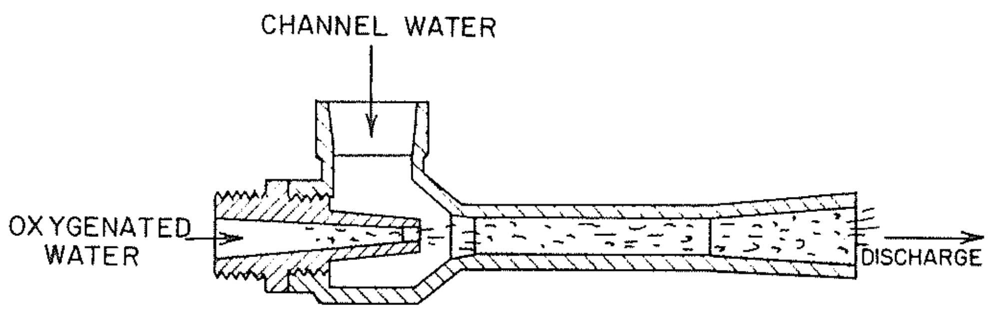

Fig. 7.10 Eductor Nozzle

that 90 percent absorption is possible. Dividing the design oxygen transfer capacities given in Table 7.3 (p.125) by 90 percent yields the maximum oxygen injection capacities. These values are given on Table 7.7. At an average annual operating capacity of 60 percent of the maximum, the average oxygen required is calculated and given in Table 7.7.

Referring to the capital and operating costs for pressure swing absorption (PSA) and cryogenic oxygen cost shown on Fig. 6.3 (p. 80) it is noted that the maximum oxygen requirements are near the breakpoint where cryogenic plants become more economical than PSA plants; but the average operating capacity is well within the PSA plant range and PSA plants are specified. The capacity of PSA plants is variable and production is governed by the pressure produced by the feed compressor (Fig. 7.11). The pressure swing absorption process is patented by Union Carbide and complete units are purchased from them on a turnkey basis. Table 7.7 lists the capacities of the PSA plants required.

Product oxygen from PSA plants is at 20 to 55 psig depending on the operating capacity and condition of the adsorption columns at the time. The oxygen pressure must be boosted to 120 psig for injection and positive displacement reciprocating compressors equipped with multispeed motors are provided for this purpose. The required drive motor horsepower, or brake horsepower, is calculated using the values in Table 7.7 and the following equation[66]:

TABLE 7.7

Capacity of PSA Plants

Site Location (1/4 mile segment)	Maximum Oxygen Injected		Average Oxygen Injected (PPD)		Capacity of PSA Unit (T/D)	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	33,840	67,943	20,304	40,766	17	34
17	62,024	67,943	37,214	40,766	31	34
29	20,816	67,943	12,490	40,766	11	34

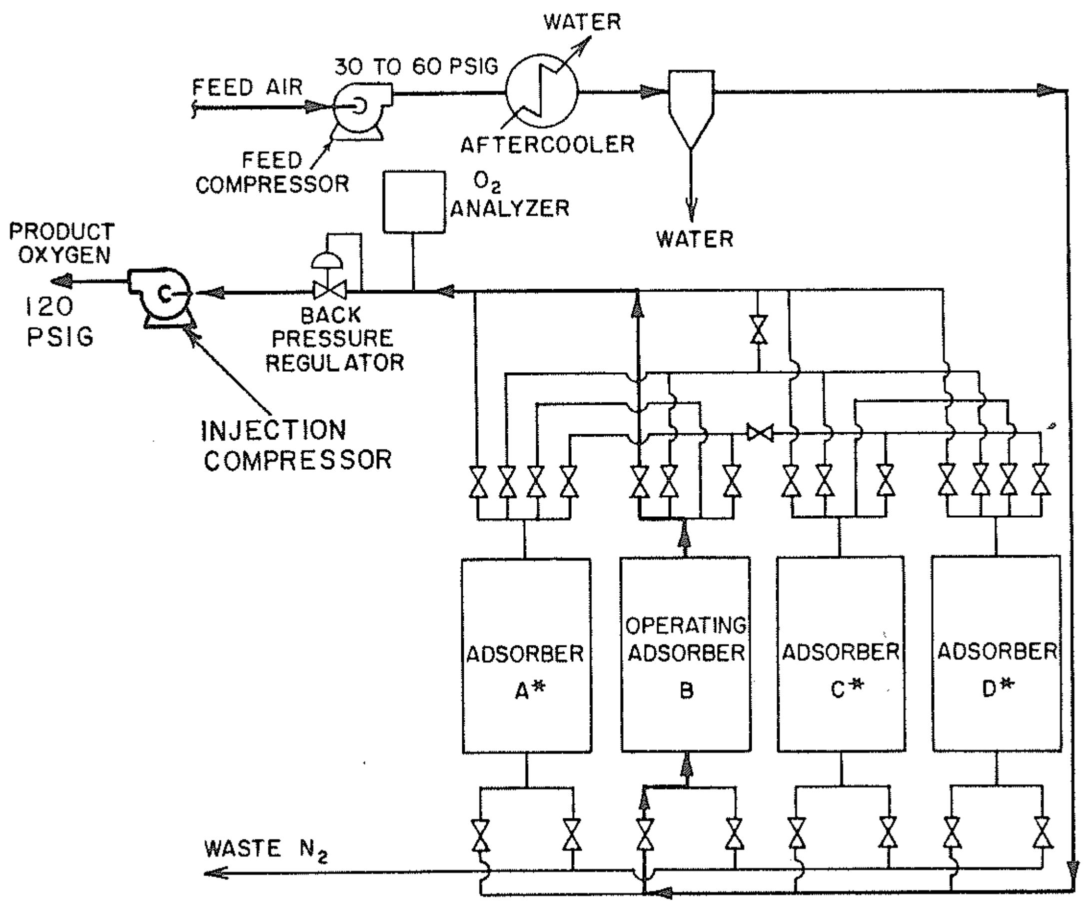

Fig. 7.11 PSA Oxygen Plant

$$\text{brake HP} = \left(\frac{W\ R\ T_1}{550\ ne} \left[\left(\frac{P_2}{P_1} \right)^{n} -1 \right] \right) 1.05 \qquad (7.6)$$

where
w = weight oxygen flow, lb/sec
R = gas constant (48.3)
T_1 = inlet temperature (^{O}R)
P_1 = inlet pressure (psia)
P_2 = outlet pressure (psia)
n = (k-1)/K (K = 1.4 for oxygen)
e = efficiency (70 percent)

The value 1.05 in equation (7.1) (p.111) increases the power requirements to account for the purity of the PSA product oxygen (95 percent). The volumetric capacity of the compressors is calculated with the generalized gas laws. Both brake horsepower and volumetric capacity of the compressors are given in Table 7.8.

Aeration systems supplied by pipeline oxygen do not require the capital outlay for a production plant, but they require extension of the existing oxygen pipeline (Fig. 6.1) (p. 70). Cost per ton of oxygen is the same for both sources. The design of the pipeline will vary with right-of-way availability, length, and currently available pressure and volume. The cost can be estimated without design and the on-site equipment is not affected by the pipeline, therefore, the scope of this report does not include design of the pipeline. It is assumed that the compressor used with on-site oxygen pressure for injection is also required with the pipeline.

System Cost

The cost analysis in Chapter VI was done without benefit of a preliminary design for the purpose of selecting systems for more detailed investigation. Having completed a preliminary design for two sidestream oxygenation systems, one using oxygen produced at

TABLE 7.8

Compressor Specifications

Site Location (1/4 mile segment)	Standard Cubic Feet per Minute		Calculated Horsepower		Drive Motor Horsepower	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	99	199	46.6	93.6	50	100
17	182	199	85.4	93.6	100	100
29	61	199	28.7	93.6	40	100

the site and the other pipeline oxygen, a unit by unit cost evaluation is undertaken.

Appendix G contains the detailed cost analysis and Table 7.9 summarizes the results. As the table indicates, the system using pipeline oxygen is approximately 10 percent less expensive annually, primarily due to a lesser initial capital outlay. Also shown on the table is cost per pound of oxygen transferred which ranges from 20 to 2.5 cents.

Table 7.10 demonstrates the difference between the first cost estimates made in Chapter VI and those made after completion of the preliminary design. The first estimates were somewhat high in all cases.

TABLE 7.9

Sidestream Oxygenation System Cost

	PSA Oxygen Plant		Pipeline Oxygen	
	2 mg/l	4 mg/l	2 mg/l	4 mg/l
Initial Cost				
1. Capital	2,153,000	2,913,000	1,730,000	2,190,000
2. Contingency(15%)	323,000	437,000	260,000	329,000
Total Initial	2,476,000	3,350,000	1,990,000	2,519,000
Annual Cost				
1. O&M				
Electrical	314,000	694,000	314,000	694,000
Oxygen	204,000	285,000	204,000	285,000
Labor	60,000	60,000	60,000	60,000
Parts	32,000	41,000	8,000	11,000
Sub Total	610,000	1,080,000	586,000	1,050,000
2. Fixed				
Interest (8%)	198,000	268,000	159,000	201,000
Deprec. (4.5%)	97,000	131,000	78,000	99,000
Sub Total	295,000	399,000	237,000	300,000
Total Annual	905,000	1,479,000	823,000	1,350,000
Cost per Pound of Oxygen Transferred	2.5¢	2.2¢	2.3¢	2.0¢

TABLE 7.10

Comparison of First and Final Cost Estimates

	Sidestream Oxygenation (PSA Oxygen Plant)		Sidestream Oxygenation (Pipeline Oxygen)	
	2 mg/l	4 mg/l	2 mg/l	4 mg/l
Initial Cost				
1. First Estimate	3,390,000	4,315,000	1,435,000	1,727,000
2. Final Estimate	2,476,000	3,350,000	1,990,000	2,519,000
Annual Cost				
1. First Estimate	1,190,000	1,722,000	1,105,000	1,580,000
2. Final Estimate	905,000	1,479,000	823,000	1,350,000

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the study:

1. In-channel supplemental aeration can increase the dissolved oxygen concentration in the Houston Ship Channel and should be considered as an alternative procedure for meeting dissolved oxygen criteria.

2. In-channel supplemental aeration, if implemented, should be provided in the upper 7.5 miles (segments zero through 30) of the channel.

3. The physical dynamics of oxygen transport dictate that the dissolved oxygen concentrations at an aeration site will be higher than the dissolved concentration between that site and the next site in an aeration system. This phenomenon is, herein, called DO build-up and is found to increase the required amount of aeration capacity by requiring a net increase in the mass of dissolved oxygen which must be present to maintain criteria. The increased system capacity required to compensate for DO build-up is found to vary from approximately 10 to 30 percent for 2 to 6 aeration sites, respectively.

4. With 1974 point source loading, the minimum oxygen required to maintain dissolved oxygen criteria of 2 mg/l in the channel during critical conditions is 71,630 pounds per day. To maintain 4 mg/l the minimum required oxygen is 133,965 pounds per day. The actual oxygen requirements for a 2 mg/l system, compensating for DO build-up, vary from 113,000 pounds per day for a 2-site system to 75,500 pounds per day for a 6-site system. A system capable of maintaining 4 mg/l dissolved oxygen

must transfer 180,000 pounds of oxygen per day if 3 sites are used and 147,000 pounds per day if 7 sites are used.

5. An aeration system capable of maintaining dissolved oxygen criteria at critical conditions can operate at reduced capacity during less demanding conditions. The average system capacity required to maintain dissolved oxygen criteria is termed average annual operating capacity, and is found to be 60 percent of the total capacity of both 2 mg/l and 4 mg/l systems.

6. Data are available to estimate the annual cost of aeration systems using surface aerators, diffused aerators, diffused oxygenators, or sidestream oxygenators based on maximum and average annual operating capacity without proceeding with preliminary design. Estimates for a 2 mg/l system arrived at by this method range from $701,000* annually for a 6-site surface aeration system to $2,922,000* annually for a 2-site diffused oxygen system supplied by a purchased oxygen storage tank. The range of annual cost for 4 mg/l systems is $1,169,000* for a 7-site surface aeration system to $4,631,000 for a diffused oxygen system with purchased oxygen tank.

7. The physical constraints imposed on in-channel aeration systems by lack of available water space in the upper channel are severe. The disadvantages created by these constraints preclude economic considerations for diffused air and surface aeration equipment.

8. Cost and physical feasibility make sidestream oxygen the most desirable equipment of the types studied for use in the upper channel.

9. On-site production and pipeline are the most economical supplies of oxygen for an oxygenation system.

* 1975 dollars

10. Maintenance, cost, and the ability to increase system capacity to meet stricter criteria are optimized in a three-site aeration system.

11. Sidestream oxygen systems are relatively new and unproven for supplemental stream aeration. However, adequate data are available for preliminary design.

12. Based on preliminary designs, the annual cost of supplemental aeration of the Houston Ship Channel using sidestream oxygenation is \$905,000* annually for a 2 mg/l system using oxygen produced on site and \$823,000* annually using oxygen supplied by a pipeline. For a 4 mg/l system the cost is \$1,479,000* annually with on-site oxygen and \$1,350,000* with pipeline oxygen. These costs are equivalent to 2.5 and 2.3 cents per pound of oxygen transferred by a 2 mg/l system using on-site and pipeline oxygen, respectively. Cost of a 4 mg/l system is 2.2 and 2.0 cents per pound of oxygen transferred for on-site and pipeline oxygen sources, respectively.

The following recommendations are made based on the study:

1. The relationship between the nitrogen decay rate and dissolved oxygen concentration is defined in this work using the limited available data. To better define the oxygen dynamics of nitrogen-polluted waters, investigations leading to more accurate definition of the relationship between nitrogen decay and dissolved oxygen should be undertaken.

2. Dispersion of oxygenated water away from aeration sites is the primary factor which determines how much DO build-up will occur. Indications are that oxygen-rich water produced by an aeration system which provides significant initial mixing disperses at a higher rate than

*1975 dollars

measured in conventional dispersion studies. Therefore, to more accurately predict DO dispersion, studies of oxygen-rich water produced by various types of aeration equipment should be made.

3. The model used herein is one-dimensional and does not consider lateral dispersion of oxygenated water. Future studies should investigate the effects of lateral dispersion on aeration systems.

4. The oxygen transfer coefficients used to design the sidestream oxygen systems are little used and unproven. Therefore, further experimentation should be undertaken to determine transfer coefficients using various contactor pipe pressures and configurations, and various amounts of injected oxygen.

5. The model used herein can be adapted to interface with stormwater runoff models. This should be done and the system redesigned before implementation.

6. Several of the convergent bayous along the upper 7.5 miles of the Houston Ship Channel provide possible extra-channel aeration sites. The methodology demonstrated herein should be used to evaluate placing aeration equipment in these bayous.

7. The cost of in-channel supplemental aeration determined herein should be compared to the cost of point source treatment and the cost of extra-channel aeration to determine which is most cost-effective.

8. The world and national economic situation is changing daily, particularly where energy is concerned, and the 1975 cost estimates given herein should be updated to the time that comparison is made between the systems examined here and other alternatives.

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APPENDIX A

MODEL

```
      COMMON        NCELLS,NM,FA,FB,FC,FD
      COMMON        A(99),B(99),C(99),H(99),S(99),UO(99),UN(99),
     1    ARO(99),ARN(99),ELO(99),ELN(99)
      DIMENSION     RBODA(99),ROXA(99),PPDBOD(99),PPDOX(99),AAER(99),
     1    OXADA(99),PPH(99),AERC(99),BENTH(99),DECAY(99),BODBAL(99),
     2    OXLOSS(99),REARN(99),OXBAL(99),OXADN(99),VOL(99),VOLN(99),
     3    BAL(99),W(99),POW(99),OXO(99),OXN(99),BODO(99),BODN(99),CO(99)
      DIMENSION     CN(99),Q(99),QN(99),TEMP(99),SAL(99),DR(99),CSAT(99),
     1    AREA(99),ETA(99),EL(99),WC(99),OXC(99),BR(99),AR(99),AAC(99),
     2BRC(99),SAREA(99),DEPTH(99),DEPTHN(99),XPLOT(99),CARB5(99),
     3CARBU(99),AMMO(99),RAMMA(99),AMMOX(99),AMMDR(99)
      DIMENSION     AMDCAY(99),PPDAOX(99),AMMBAL(99),AMMN(99),AMM(99),
     1TPPD(99),AER(99),AE(99),AWC(99),DC(99),AMMDC(99),AMDR(99)
     2,ANARDR(99),ANARDC(99),IFLAG(99),ICOUNT(99),OXOLD(99),BODNN(99),
     3AMMNN(99)
      DATA DOC/'O'/,BODC/'*'/,AMMC/'+'/
      READ(5,1001) NCELLS,NCYCLE,NTSPC
 1001 FORMAT(3I10)
      NP = NCELLS+1
      NM = NCELLS-1
C     --------------RED-------------------------------------------
C         INPUT DATA
C     ------------------------------------------------------------
      WRITE(6,1015)
 1015 FORMAT(1H1,7X,'SEG',3X,'AREA',8X,'VOL',7X,'W',8X,'DEPTH',5X,
     1'SAREA')
      DO   1 I=1,NP
      READ(5,1020) J,AREA(J),VOL(J),W(J),DEPTH(J),SAREA(J)
      WRITE(6,1020)J,AREA(J),VOL(J),W(J),DEPTH(J),SAREA(J)
    1 CONTINUE
      WRITE (6,1016)
 1016 FORMAT (1H1,7X,'SEG.',3X,'TEMP',7X,'SAL',7X,'EL',9X,'BR',8X,'DC',
     16X,'AMMDC')
      DO 101 I=1,NP
      READ (5,1020)J,TEMP(J),SAL(J),EL(J),BR(J),DC(J),AMMDC(J)
      WRITE (6,1020)J,TEMP(J),SAL(J),EL(J),BR(J),DC(J),AMMDC(J)
  101 CONTINUE
      READ (5,1002) D,DELX,CR,T,AO,LAGT
      READ (5,1002)THETA,BETA,AC
      READ (5,1002) OXOUT,BODOUT,AMMOUT
 1002 FORMAT(6F10.2)
      WRITE (6,1017)BODOUT,AMMOUT,OXOUT
 1017 FORMAT (1H1,7X,'SEG.',4X,'BODO',6X,'AMMO',6X,'OXO',3F10.2)
      DO 102 I=1,NP
      READ (5,1020)J,BODO(J),AMMO(J),OXO(J)
      WRITE(6,1020)J,BODO(J),AMMO(J),OXO(J)
  102 CONTINUE
 1020 FORMAT(I10,7F10.2)
```

```
C       -------------BLUE-----------------------------------------
C          INITIALIZE AREAS AND DISPERSION COEFFICIENTS
C       ----------------------------------------------------------
        DO  2 I=1,NP
        Q(I) = 0.0
        WC(I) = 0.0
        AWC(I) = 0.0
        OXC(I) = 0.0
        PPH(I) = 0.0
        OXADA(I) = 0.0
        RBODA(I) = 0.0
        RAMMA(I)=0.0
        ROXA(I) = 0.0
        PPDBOD(I) = 0.0
        PPDOX(I) = 0.0
        AAER(I) = 0.0
        AAC(I) = 0.0
        AERC(I) = 0.0
        POW(I) = 0.0
        CARB5(I)=0.0
        AMM(I)=0.0
        IFLAG(I) = 1
        ICOUNT(I) = 0
        OXOLD(I) = 0.3
        SAREA(I) = SAREA(I)*1000000.0
        DR(I) = DC(I)*(1.047**(TEMP(I)-20.0))/86400.
        AMDR(I) = AMMDC(I)*(1.09**(TEMP(I)-20.0))
        ANARDR(I) = (0.15*DC(I))*(1.047**(TEMP(I)-20.0))/86400.
        CSAT(I) = 14.652-0.41022*TEMP(I) + 0.007991*TEMP(I)*TEMP(I) -
       1   0.000077774*TEMP(I)*TEMP(I)*TEMP(I)-SAL(I)*(0.0841-0.00256*
       2   TEMP(I)+0.0000374*TEMP(I)*TEMP(I))
        BRC(I) = BR(I)*(1.055**(TEMP(I)-32.0))/17578751.0
        ARO(I) = AREA(I)
        ELO(I) = EL(I)
      2 CONTINUE
        READ(5,1020)  NIF
        TQ = 0.0
        TCARBU = 0.0
        TAMMOX = 0.0
        WRITE (6,1026)
   1026 FORMAT (1H1,T33,'INFLUENT QUAN/QUAL')
        WRITE (6,1027)
   1027 FORMAT (1H ,T33,'-----------------')
        WRITE (6,1023)
   1023 FORMAT (1H0,T20,'SEG.',6X,'Q',5X,'CARB. BOD5',4X,'NH3-N',8X,'DO')
        WRITE (6,1024)
   1024 FORMAT (1H ,T28,'(CFS)',6X,'(PPD)',6X,'(PPD)',6X,'(PPM)')
        DO 3 I=1,NIF
        READ(5,1020) J,Q(J),CARB5(J),AMM(J),OXC(J)
        WRITE(6,1025) J,Q(J),CARB5(J),AMM(J),OXC(J)
        CARBU(J)=CARB5(J)*1.5
        AMMOX(J) = AMM(J)*3.63
        QQ = Q(J)
        IF (QQ .LE. 0.0) QQ=0.01
        WC(J) = CARBU(J)*0.755/(5.4*QQ)
        AWC(J) = AMMOX(J)*0.755/(5.4*QQ)
        TCARBU = TCARBU+CARBU(J)
        TQ = TQ+Q(J)
```

```
      TAMMOX = TAMMOX+AMMOX(J)
      TLOAD = TCARBU+TAMMOX
    3 CONTINUE
 1025 FORMAT (19X,I2,3X,F8.2,3X,F8.2,3X,F8.2,6X,F5.2)
      WRITE (6,1018) TQ
 1018 FORMAT (1H0,T20,'TOTAL FLOW = ',F7.2,' CFS')
      WRITE(6,1019) TCARBU
 1019 FORMAT(1H ,T20,'CARB. BODU LOAD = ',F10.2,' PPD')
      WRITE (6,1021) TAMMOX
 1021 FORMAT (1H ,T20,'NIT. BODU LOAD  = ',F10.2,' PPD')
      WRITE (6,1022) TLOAD
 1022 FORMAT (1H ,T20,'TOTAL BODU LOAD = ',F10.2,' PPD')
      READ(5,1020)  NAS
      IF(NAS.EQ.0) GO TO 4
      DO   4 I=1,NAS
      READ(5,1020) J,POW(J)
      AAC(J) = AC*POW(J)*(1.025**(TEMP(J)-20.0))*BETA/(9.17*3600.)
    4 CONTINUE
C     ------------------------------------------------------------------
C        CALCULATE CONSTANTS FOR VELOCITY CALCULATIONS
C     ------------------------------------------------------------------
      T = T*3600.
      AO = AO/4.0
      SPC = NTSPC
      DELT = T/SPC
      PS = SQRT(32.17*D)
      WL = PS*T
      WNO = 6.2832/WL
      WN = WNO/CR
      GNU = WNO*(SQRT(1.0/CR/CR - 1.0))
      ALPHA = ATAN(GNU/WN)
      SIGMA = 6.2832/T
      F1 = SQRT(GNU*GNU + WN*WN)
      F1 = AO*PS*WNO/F1
      F2 = EXP(-GNU*DELX)
      F3 = EXP( GNU*DELX)
C     --------------GREEN-----------------------------------------------
C        CALCULATE CONSTANTS FOR DISPERSION EQUATION
C     ------------------------------------------------------------------
      FA = DELT*THETA/( DELX*2.0 )
      FB = DELT*THETA/(DELX*DELX*2.0)
      FC = DELT*(1.0-THETA)/(DELX*2.0)
      FD = DELT*(1.0-THETA)/(DELX*DELX*2.0)
C     ------------------------------------------------------------------
C        CALCULATE INITIAL VELOCITIES
C     ------------------------------------------------------------------
      QN(1) = Q(1)
      UO(1) = QN(1)/ARO(1)
      DO 5 I=2,NP
      QN(I) = QN(I-1) + Q(I)
      UO(I) = QN(I)/ARO(I)
    5 CONTINUE
C     ------------------------------------------------------------------
C        START TIME STEPS FOR CALCULATIONS
C     ------------------------------------------------------------------
      DO 16 I=1,NCYCLE
      DO 15 J=1,NTSPC
      E = '
```

```
      TIME = DELT*E
      FE = SIGMA*TIME
C     --------------YELLOW-------------------------------------------
C        CALCULATE TIDE HEIGHTS AND AREAS
C     ---------------------------------------------------------------
      DO 6 K=1,NP
      EE = K
      X = DELX*EE - DELX
      ETA(K) = AO*(EXP(-GNU*X)*COS(FE-WN*X) + EXP(GNU*X)*COS(FE+WN*X))
      ARN(K) = AREA(K) + W(K)*ETA(K)
      DEPTHN(K) = DEPTH(K) + ETA(K)
    6 CONTINUE
C     --------------RED----------------------------------------------
C        CALCULATE VELOCITIES AND DISPERSION COEFFICIENTS
C     ---------------------------------------------------------------
      F4 = FE-WN*DELX+ALPHA
      F5 = FE+WN*DELX+ALPHA
      QN(1) = Q(1)+(SAREA(1)/DELX)*(F1*(F2*COS(F4)-F3*COS(F5)))
      UN(1) = QN(1)/ARN(1)
      ELN(1) = EL(1)-(UN(1)/2.0)*(DELX-UN(1)*DELT)
      DO 7 K=2,NP
      QN(K) = QN(K-1)+Q(K)+(SAREA(K)/DELX)*(F1*(F2*COS(F4)-F3*COS(F5)))
      UN(K) = QN(K)/ARN(K)
      ELN(K) = EL(K)-(UN(K)/2.0)*(DELX-UN(K)*DELT)
    7 CONTINUE
C     --------------BLUE---------------------------------------------
C        CALCULATE RATE OF ADDITION OF CONTAMINANTS AND BOD BALANCE
C     ---------------------------------------------------------------
      DO 9 K=1,NCELLS
      CONC = (OXO(K)+OXO(K+1))/2.0
      VOLN(K) = VOL(K)*1000000.0 + W(K)*ETA(K)*DELX
      VEL=UN(K)
      IF(VEL.LE.0.0)VEL=-VEL
      AER(K) = (4/DEPTH(K))+((165.02*VEL)**0.5)/(DEPTH(K)**1.5)
      AE(K)=(AER(K)*(1.047**(TEMP(K)-20.0)-0.059*SQRT(SAL(K))))
      AR(K)=AE(K)/86400.
      REARN(K) = AR(K)*(CSAT(K)-CONC)
      AAER(K) = AAC(K)*(CSAT(K)-CONC)*1000000./(VOLN(K)*62.4)
      ROXA(K) = Q(K)*OXC(K)/VOLN(K)
      BENTH(K) = BRC(K)*W(K)*DELX*1000000./(VOLN(K)*62.4)
      RBODA(K) = Q(K)*WC(K)/VOLN(K)
      RAMMA(K)=Q(K)*AWC(K)/VOLN(K)
      DECAY(K) = DR(K)*(BODO(K)+BODO(K+1))/2.0
      TEST = DECAY(K)*DELT
      IF(TEST .LT. CONC) GOTO 99
      DECAY(K) = CONC/DELT
   99 CONTINUE
      IF (K .EQ. 1) GOTO 30
      IF (J .EQ. NTSPC) GOTO 20
      GOTO 30
   20 IF (OXOLD(K) .LE. 0.02 .AND. CONC .GT. 0.02) IFLAG(K) = 2
      OXOLD(K) = CONC
      IF (IFLAG(K) .GT. 1) ICOUNT(K) = ICOUNT(K)+1
      IF (ICOUNT(K) .GT. LAGT) IFLAG(K) = 1
      IF (1-IFLAG(K)) 40,30,30
   30 AMMOR(K) = (1.143*AMOR(K)*CONC)/(1.4+CONC)
      GOTO 50
   40 AMMOR(K) = 0.0
```

```
   50 CONTINUE
      AMDCAY(K) = (AMMDR(K)/86400.)*(AMMO(K)+AMMO(K+1))/2.0
      ANARDC(K) = ANARDR(K)*(BODO(K)+BODO(K+1))/2.0
      IF (CONC .GT. 0.2) ANARDC(K)=0.0
      OXLOSS(K)=(DECAY(K)+BENTH(K)+AMDCAY(K))*86400.0*VOLN(K)*0.0000624
      BODBAL(K) = (RBODA(K)-DECAY(K)-ANARDC(K))*DELT
      OXBAL(K) = (ROXA(K)+AAER(K)+REARN(K)-DECAY(K)-BENTH(K)-AMDCAY(K))
     2*DELT
      AMMBAL(K)=(RAMMA(K)-AMDCAY(K))*DELT
      OXADA(K) = AAER(K)*86400.*VOLN(K)*0.0000624
      OXADN(K) = REARN(K)*86400.*VOLN(K)*0.0000624
      PPH(K) = OXADA(K)/24.0
      BODNN(K) = BODN(K)/1.5
      AMMNN(K) = AMMN(K)/3.63
      IF(POW(K) .EQ. 0.0 ) GOTO 9
      AERC(K) = PPH(K)/POW(K)
    9 CONTINUE
      CALL SOLVE (BODBAL,BODO,BODN,BODOUT)
      CALL SOLVE (AMMBAL,AMMO,AMMN,AMMOUT)
      CALL SOLVE (OXBAL,OXO,OXN,OXOUT)
C     -------------GREEN---------------------------------------
C        WRITE ANSWERS
C     ---------------------------------------------------------
      IF (J .EQ. NTSPC) GOTO 11
      GOTO 13
   11 WRITE (6,1006)
 1006 FORMAT (1H1,T33,'CHANNEL QUALITY')
      WRITE (6,1007)
 1007 FORMAT(1H ,T33,'---------------')
      WRITE (6,1003)
 1003 FORMAT (1H0,T21,'SEG.',3X,'CARB. BODU',3X,'NIT. BODU',7X,'DO')
      WRITE (6,1004) I,J
 1004 FORMAT (1H ,T31,'(PPM)',7X,'(PPM)',7X,'(PPM)',10X,2I6)
      DO 12 K=1,NCELLS
      P=K
      IF (K/2 .NE. P/2.0) GOTO 12
      WRITE (6,1005) K,BODN(K),AMMN(K),OXN(K),AER(K),AMMDR(K)
   12 CONTINUE
 1005 FORMAT (21X,I2,6X,F6.2,6X,F6.2,6X,F6.2,15X,F6.3,3X,F6.3)
      WRITE (6,1008) I
 1008 FORMAT (1H0,T21,'NO. OF TIDAL CYCLES = ',I3)
      WRITE (6,1009)
 1009 FORMAT (1H ,T21,'AVG. TIME PER CYCLE = 24.84    HR')
      WRITE (6,1011)
 1011 FORMAT (1H1,T15,'K      IFLAG      ICOUNT      OXBAL      OXOLD
     1 AMMDR')
      DO 125 K = 1,NCELLS
      WRITE (6,1010) K,IFLAG(K),ICOUNT(K), OXBAL(K),OXOLD(K),AMMDR(K)
  125 CONTINUE
 1010 FORMAT (15X,3I6,3F10.4)
   13 DO 14 K=1,NP
      BODO(K) = BODN(K)
      IF(BODO(K) .LT. 0.0 ) BODO(K) = 0.0
      OXO(K) = OXN(K)
      IF( OXO(K) .LT. 0.0 )  OXO(K) = 0.0
      AMMO(K)=AMMN(K)
      IF(AMMO(K) .LT. 0.0) AMMO(K)=0.0
      UO(K) = UN(K)
```

```
      ELO(K) = ELN(K)
      ARO(K) = ARN(K)
   14 CONTINUE
   15 CONTINUE
   16 CONTINUE
      DO 65 J=1,NCELLS
   65 XPLOT(J)=J
      XMIN=0
      XMAX=60.0
      YMIN=0
      YMAX=5.0
      YMAX2 = 10.0
      YINC = 0.5
      YINC2 = 1.0
      CALL GRAPH (51,108,XPLOT,OXN,NCELLS)
      CALL LABEL (YMAX,YMIN,YINC)
      CALL GRAPHB (NCELLS,OXN,XPLOT,DOC,XMAX,XMIN,YMAX,YMIN)
      CALL GRAPHC
      CALL GRAPH (51,108,XPLOT,BODNN,NCELLS)
      CALL LABEL (YMAX2,YMIN,YINC2)
      CALL GRAPHB (NCELLS,BODNN,XPLOT,BODC,XMAX,XMIN,YMAX2,YMIN)
      CALL GRAPHC
      CALL GRAPH (51,108,XPLOT,AMMNN,NCELLS)
      CALL LABEL (YMAX2,YMIN,YINC2)
      CALL GRAPHB (NCELLS,AMMNN,XPLOT,AMMC,XMAX,XMIN,YMAX2,YMIN)
      CALL GRAPHC
      STOP
      END
```

```
C     ------------------------------------------------------------------
      SUBROUTINE SOLVE (BAL,CO,CN,CLAST)
C     ------------------------------------------------------------------
      COMMON       NCELLS,NM,FA,FB,FC,FD
      COMMON       A(99),B(99),C(99),H(99),S(99),UO(99),UN(99),
     1   ARO(99),ARN(99),ELO(99),ELN(99)
      DIMENSION BAL(99),CO(99),CN(99)
C     ------------------------------------------------------------------
C        CALCULATE COEFFICIENTS FOR THE DISPERSION EQUATION
C     ------------------------------------------------------------------
      A(1) = -FA*UN(1) - FB*ELN(1)
      B(1) = 1.0 + FA*UN(1)*ARN(2)/ARN(1) + FB*(ARN(2)*ELN(2)
     1   + 2.0*ARN(1)*ELN(1))/ARN(1)
      C(1) = FA*UN(1) -FB*(ARN(2)*ELN(2) + ARN(1)*ELN(1))/ARN(1)
      H(1) = CO(1)-FC*UO(1)*CO(2)+FC*UO(1)*CO(1)*ARO(2)/ARO(1)
     1   +FD*(ARO(2)*ELO(2)+ARO(1)*ELO(1))*(CO(2)-CO(1))/ARO(1)
     2   -FD*ELO(1)*CO(1) + BAL(1)
      DO 1 K=2,NCELLS
      A(K) = -FA*UN(K)-FB*(ARN(K)*ELN(K)+ARN(K-1)*ELN(K-1))/ARN(K)
      B(K) = 1.0+FA*UN(K)*(ARN(K+1)-ARN(K-1))/ARN(K) + FB*
     1   (ARN(K+1)*ELN(K+1)+2.0*ARN(K)*ELN(K)+ARN(K-1)*ELN(K-1))/ARN(K)
      C(K) = FA*UN(K)-FB*(ARN(K+1)*ELN(K+1)+ARN(K)*ELN(K))/ARN(K)
      H(K) = CO(K)-FC*UO(K)*(CO(K+1)-CO(K-1))+FC*UO(K)*CO(K)*(ARO(K+1)
     1   -ARO(K-1))/ARO(K) + FD*(ARO(K+1)*ELO(K+1)+ARO(K)*ELO(K))*
     2   (CO(K+1)-CO(K))/ARO(K) - FD*(ARO(K)*ELO(K)+ARO(K-1)*ELO(K-1))*
     3   (CO(K)-CO(K-1))/ARO(K) + BAL(K)
    1 CONTINUE
      NP = NCELLS + 1
      CO(NP) = CLAST
      CN(NP) = CLAST
C     ------------------------------------------------------------------
C        SET UP SOLUTION MATRIX COEFFICIENTS
C     ------------------------------------------------------------------
      DO 2 K=2,NCELLS
      S(K) = B(K-1)/A(K)
      H(K) = H(K)*S(K)-H(K-1)
      B(K) = B(K)*S(K)-C(K-1)
      C(K) = C(K)*S(K)
    2 CONTINUE
C     ------------------------------------------------------------------
C        SOLVE FOR NEW CONCENTRATIONS
C     ------------------------------------------------------------------
      DO 3  K=1,NM
      CN(NP-K) = (H(NP-K)-CN(NP-K+1)*C(NP-K))/B(NP-K)
    3 CONTINUE
      CN(1) = (H(1)-CN(3)*(C(1)+A(1)))/B(1)
      RETURN
      END
```

APPENDIX B

T.W.Q.B DISCHARGE DATA

Name	T.W.Q.B WCO Number	HYDRAULIC LOAD (MGD) Discharge	Runoff Low	Runoff Normal	WASTE LOAD (PPD) NH_3-N	BOD_5
Buffalo Bayou			28.0	285.0		1,600
Houston	10495-01	71.6			10,446	56,397
Houston	10495-30	9.8			1,181	2,817
Houston	10495-76	4.5			316	356
Cook Point	00427					485
Agriculture		0.6			5	5
Undesignated		3.7				248
Undesignated		0.2				54
Brays Bayou			25.0	95.0		1,200
Houston	10495-37	22.2			1,463	1,533
Agriculture		0.2				2
Undesignated		5.8				578
Charter-International	00535	1.7			2,572	907
Undesignated		1.0				112
Undesignated		0.6				84
Sims Bayou			16.0	63.0		970
Houston	10495-02	38.2			2,552	16,961
Houston	10495-09	3.5			483	1,210
Houston	10495-53	1.9			32	304
Goodyear	00520	2.4			1,980	384
Petro-Tex*	00587	4.2			387	3,000
Sinclair Koppers	00393	0.5			20	504
South Houston	10287-0-	2.4			348	380

Name	T.W.Q.B. WCO Number	HYDRAULIC LOAD (MGD) Discharge	Runoff Low	Runoff Normal	WASTE LOAD (PPD) NH_3-N	BOD_5
Agriculture		0.2				2
Undesignated		5.9				877
Atlantic-Richfield*	00392					
G.A.T.X.	01586	0.1				429
Vince Bayou			0.6	12.0		18
Pasadena	11053-01&05	4.0			410	1,245
Pasadena	10053-03	1.8			225	225
Undesignated		1.2				192
Premier Pet.	01045	0.0			275	100
Crown Central*	00574					
Champion-Papers*	00640					
G.C.A.		39.0			3,706	14,850
Hunting Bayou			3.7	7.8		120
Undesignated		3.3				714
G.A.T.X.	01308	0.2			8	407
Undesignated		2.4				112
Green Bayou			13.0	110.0		840
Houston	10495-16	1.4			60	282
Reichold Chem.	00662	0.1			88	36
Agriculture		0.2				2
Undesignated		6.5				1,391
Phillips Pet.	00815	0.9			444	163
Pasadena	10053-02	2.7			62	77

Name	T.W.Q.B. WCO Number	HYDRAULIC LOAD (MGD) Discharge	Runoff Low	Runoff Normal	WASTE LOAD (PPD)	BOD_5
Ethyl Corp.	00492	3.9			157	741
Undesignated		0.6				167
Tenneco Chem.	00002	2.5			1,350	593
Undesignated		0.6				167
Shell Oil	00403	3.2			656	566
Undesignated		0.2				41
Southland-Paper	01160	10.5			261	1,157
Patrick-Bayou			3.3	4.5		300
Lubrrzol	00639-01	0.7			276	49
Diamond Shamrock	00305	12.7			3,114	2,703
Shell Chem.	00402	5.9			977	1,923
Undesignated		0.6				156
Tucker Bayou			3.2	4.5		290
Rohm&Haas	00458	1.0			3,000	1,688
Rollins	01429	0.3			50	338
Undesignated		0.2				186
Carpenters Bayou			0.6	16.0		38
Undesignated		1.4				144

*All are part of the waste going to the Gulf Coast Authority (G.C.A.) plant.

APPENDIX C

CHANNEL DIMENSIONS

SEG	AREA	VOL	W	DEPTH	SAREA
1	18000.00	55.20	1100.00	38.00	7.52
2	16000.00	19.30	400.00	37.00	1.47
3	14500.00	21.40	450.00	36.00	0.52
4	18000.00	24.10	530.00	34.00	0.59
5	18500.00	24.80	520.00	36.00	0.70
6	19000.00	24.40	510.00	36.00	0.69
7	18000.00	25.80	580.00	33.00	0.67
8	21000.00	32.00	900.00	27.00	0.77
9	26000.00	35.00	940.00	28.00	2.46
10	24000.00	28.50	600.00	35.00	3.74
11	18000.00	22.40	480.00	35.00	0.81
12	14000.00	21.20	750.00	21.00	0.64
13	14000.00	21.20	790.00	20.00	0.99
14	16500.00	20.40	520.00	30.00	1.04
15	17000.00	22.70	570.00	32.00	1.14
16	16500.00	24.50	610.00	32.00	0.75
17	17500.00	54.00	1290.00	34.00	2.68
18	18000.00	43.00	880.00	37.00	1.70
19	18000.00	25.50	570.00	33.00	1.16
20	17000.00	25.00	640.00	30.00	0.75
21	17000.00	37.30	850.00	33.00	0.84
22	17000.00	25.10	780.00	24.00	1.13
23	16500.00	24.40	760.00	24.00	1.06
24	16000.00	24.20	700.00	26.00	1.00
25	16500.00	26.30	730.00	27.00	0.92
26	16000.00	22.70	670.00	26.00	0.96
27	16500.00	23.10	670.00	26.00	0.89
28	17500.00	26.10	780.00	25.00	0.89
29	18000.00	37.00	1230.00	30.00	1.58
30	20000.00	26.80	760.00	27.00	2.54
31	17500.00	23.40	550.00	32.00	1.00
32	16000.00	33.70	800.00	32.00	0.72
33	18000.00	31.50	760.00	31.00	1.05
34	17500.00	29.10	1040.00	21.00	1.01
35	16500.00	22.70	660.00	26.00	1.38
36	15500.00	32.00	780.00	31.00	0.87
37	16500.00	34.10	860.00	30.00	1.40
38	18000.00	29.40	1110.00	20.00	9.90
39	22000.00	29.30	1220.00	18.00	1.47
40	20000.00	27.30	1480.00	14.00	1.61
41	17000.00	26.60	1090.00	18.00	1.95
42	20000.00	31.30	1240.00	19.00	1.44
43	20000.00	28.20	730.00	29.00	1.64
44	17000.00	28.70	920.00	24.00	0.97
45	20000.00	32.40	1220.00	20.00	1.22
46	20000.00	28.50	1200.00	18.00	1.61
47	20000.00	42.80	1000.00	32.00	1.59
48	28000.00	60.60	1390.00	34.00	2.66
49	32000.00	56.80	1350.00	32.00	1.33
50	27000.00	35.90	860.00	31.00	1.78
51	20500.00	42.20	1030.00	31.00	1.14
52	22000.00	45.00	1100.00	31.00	1.36
53	22500.00	42.50	1480.00	22.00	3.87
54	26000.00	37.10	1200.00	24.00	1.95
55	20500.00	36.00	1180.00	27.00	1.58
56	23000.00	35.10	1060.00	25.00	4.74
57	20500.00	34.50	1320.00	20.00	2.46
58	21000.00	43.20	1400.00	23.00	1.75
59	21000.00	34.00	1900.00	14.00	3.64
60	20500.00	33.40	1270.00	20.00	2.50

APPENDIX D

DETAIL COST SHEETS

TOTAL COST SHEET

SIDESTREAM, PIPELINE, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,220,000	1,248,000	1,265,000	1,320,000
2. Contingency 15%	183,000	187,000	190,000	198,000
TOTAL INITIAL	1,403,000	1,435,000	1,455,000	1,518,000
ANNUAL COST				
1. O & M				
Electrical	410,000	378,000	332,000	274,000
Oxygen	504,000	471,000	428,000	375,000
Labor	40,000	60,000	80,000	120,000
Parts	24,000	25,000	25,000	26,000
SUB TOTAL	978,000	934,000	865,000	795,000
2. Fixed				
Interest (8%)	112,000	115,000	116,000	121,000
Deprec. (4.5%)	55,000	56,000	57,000	59,000
SUB TOTAL	167,000	171,000	173,000	180,000
TOTAL ANNUAL	1,145,000	1,105,000	1,038,000	975,000

TOTAL COST SHEET

SIDESTREAM, PIPELINE, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	1,502,000	1,540,000	1,577,000	1,628,000
2. Contingency 15%	225,000	231,000	237,000	244,000
TOTAL INITIAL	1,727,000	1,771,000	1,814,000	1,872,000
ANNUAL COST				
1. O & M				
Electrical	653,000	631,000	545,000	533,000
Oxygen	631,000	615,000	548,000	540,000
Labor	60,000	80,000	120,000	140,000
Parts	30,000	31,000	32,000	33,000
SUB TOTAL	1,374,000	1,357,000	1,245,000	1,246,000
2. Fixed				
Interest (8%)	138,000	142,000	145,000	150,000
Deprec. (4.5%)	68,000	69,000	71,000	73,000
SUB TOTAL	206,000	211,000	216,000	223,000
TOTAL ANNUAL	1,553,000	1,568,000	1,461,000	1,469,000

TOTAL COST SHEET

SIDESTREAM, PURCHASE TANK, 2 mg/l

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,411,000	1,457,000	1,452,000	1,485,000
2. Contingency 15%	212,000	219,000	218,000	223,000
TOTAL INITIAL	1,623,000	1,676,000	1,670,000	1,708,000
ANNUAL COST				
1. O & M				
Electrical	410,000	378,000	332,000	274,000
Oxygen	744,000	685,000	608,000	499,000
Labor	40,000	60,000	80,000	120,000
Parts	24,000	25,000	25,000	26,000
SUB TOTAL	1,218,000	1,148,000	1,045,000	919,000
2. Fixed				
Interest (8%)	130,000	134,000	134,000	137,000
Deprec. (4.5%)	64,000	66,000	65,000	67,000
SUB TOTAL	194,000	200,000	199,000	204,000
TOTAL ANNUAL	1,412,000	1,348,000	1,244,000	1,123,000

TOTAL COST SHEET

SIDESTREAM, PURCHASE TANK, 4 mg/l

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	1,826,000	1,862,000	1,891,000	1,935,000
2. Contingency 15%	274,000	279,000	284,000	290,000
TOTAL INITIAL	2,100,000	2,141,000	2,175,000	2,225,000
ANNUAL COST				
1. O & M				
Electrical	653,000	631,000	545,000	533,000
Oxygen	1,183,000	1,143,000	989,000	966,000
Labor	60,000	80,000	120,000	140,000
Parts	36,000	37,000	38,000	39,000
SUB TOTAL	1,932,000	1,891,000	1,692,000	1,678,000
2. Fixed				
Interest (8%)	168,000	171,000	174,000	178,000
Deprec. (4.5%)	82,000	84,000	85,000	87,000
SUB TOTAL	250,000	255,000	259,000	265,000
TOTAL ANNUAL	2,182,000	2,145,000	1,951,000	1,943,000

TOTAL COST SHEET

SIDESTREAM, RENT TANK, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,226,000	1,257,000	1,277,000	1,338,000
2. Contingency 15%	184,000	189,000	192,000	201,000
TOTAL INITIAL	1,410,000	1,446,000	1,469,000	1,539,000
ANNUAL COST				
1. O & M				
Electrical	410,000	378,000	332,000	274,000
Oxygen	744,000	685,000	608,000	499,000
Labor	40,000	60,000	80,000	120,000
Parts	25,000	25,000	26,000	27,000
SUB TOTAL	1,219,000	1,148,000	1,046,000	920,000
2. Fixed				
Interest (8%)	113,000	116,000	118,000	123,000
Deprec. (4.5%)	55,000	57,000	58,000	60,000
SUB TOTAL	168,000	173,000	176,000	183,000
TOTAL ANNUAL	1,387,000	1,321,000	1,222,000	1,103,000

TOTAL COST SHEET

SIDESTREAM, RENT TANK, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	1,511,000	1,552,000	1,595,000	1,649,000
2. Contingency 15%	277,000	233,000	239,000	247,000
TOTAL INITIAL	1,738,000	1,785,000	1,834,000	1,896,000
ANNUAL COST				
1. O & M				
Electrical	653,000	631,000	545,000	533,000
Oxygen	1,183,000	1,143,000	989,000	966,000
Labor	60,000	80,000	120,000	140,000
Parts	30,000	31,000	32,000	33,000
SUB TOTAL	1,926,000	1,885,000	1,685,000	1,672,000
2. Fixed				
Interest (8%)	139,000	143,000	147,000	152,000
Deprec. (4.5%)	68,000	70,000	72,000	74,000
SUB TOTAL	207,000	213,000	219,000	226,000
TOTAL ANNUAL	2,133,000	2,098,000	1,905,000	1,898,000

TOTAL COST SHEET

SIDESTREAM, PURCHASE PLANT, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	2,670,000	2,948,000	2,665,000	2,820,000
2. Contingency 15%	401,000	442,000	400,000	423,000
TOTAL INITIAL	3,071,000	3,390,000	3,065,000	3,243,000
ANNUAL COST				
1. O & M				
Electrical	410,000	378,000	332,000	274,000
Oxygen	314,000	289,000	267,000	226,000
Labor	40,000	60,000	80,000	120,000
Parts	53,000	59,000	53,000	56,000
SUB TOTAL	817,000	786,000	732,000	676,000
2. Fixed				
Interest (8%)	256,000	271,000	245,000	259,000
Deprec. (4.5%)	120,000	133,000	120,000	127,000
SUB TOTAL	376,000	404,000	365,000	386,000
TOTAL ANNUAL	1,193,000	1,190,000	1,097,000	1,062,000

TOTAL COST SHEET

SIDESTREAM, PURCHASE PLANT, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	3,752,000	3,840,000	3,777,000	3,878,000
2. Contingency 15%	563,000	576,000	567,000	519,000
TOTAL INITIAL	4,315,000	4,416,000	4,344,000	4,397,000
ANNUAL COST				
1. O & M				
Electrical	653,000	631,000	545,000	533,000
Oxygen	421,000	407,000	372,000	365,000
Labor	60,000	80,000	120,000	140,000
Parts	74,000	77,000	76,000	78,000
SUB TOTAL	1,208,000	1,195,000	1,113,000	1,116,000
2. Fixed				
Interest (8%)	345,000	353,000	348,000	352,000
Deprec. (4.5%)	169,000	173,000	170,000	177,000
SUB TOTAL	514,000	526,000	518,000	529,000
TOTAL ANNUAL	1,722,000	1,721,000	1,631,000	1,645,000

TOTAL COST SHEET

DIFFUSED AERATION, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,897,000	2,047,000	1,969,000	2,009,000
2. Contingency 15%	285,000	307,000	295,000	301,000
TOTAL INITIAL	2,182,000	2,354,000	2,264,000	2,310,000
ANNUAL COST				
1. O & M				
Electrical	606,000	558,000	491,000	405,000
Oxygen				
Labor	40,000	60,000	80,000	120,000
Parts	38,000	41,000	39,000	40,000
SUB TOTAL	684,000	659,000	610,000	565,000
2. Fixed				
Interest (8%)	175,000	188,000	181,000	185,000
Deprec. (9%)	171,000	184,000	177,000	181,000
SUB TOTAL	346,000	372,000	358,000	366,000
TOTAL ANNUAL	1,036,000	1,031,000	968,000	931,000

TOTAL COST SHEET

DIFFUSED AERATION, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	3,557,000	3,449,000	3,388,000	3,486,000
2. Contingency 15%	534,000	517,000	508,000	523,000
TOTAL INITIAL	4,091,000	3,966,000	3,896,000	4,009,000
ANNUAL COST				
1. O & M				
Electrical	964,000	932,000	804,000	788,000
Oxygen				
Labor	60,000	80,000	120,000	140,000
Parts	71,000	69,000	68,000	70,000
SUB TOTAL	1,095,000	1,081,000	992,000	998,000
2. Fixed				
Interest (8%)	327,000	317,000	312,000	321,000
Deprec. (9%)	320,000	310,000	305,000	314,000
SUB TOTAL	647,000	627,000	617,000	635,000
TOTAL ANNUAL	1,742,000	1,708,000	1,609,000	1,633,000

TOTAL COST SHEET

SURFACE AERATION, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,411,000	1,341,000	1,304,000	1,281,000
2. Contingency 15%	212,000	201,000	196,000	192,000
TOTAL INITIAL	1,623,000	1,542,000	1,500,000	1,473,000
ANNUAL COST				
1. O & M				
Electrical	308,000	283,000	249,000	206,000
Oxygen				
Labor	40,000	60,000	80,000	120,000
Parts	11,000	27,000	26,000	26,000
SUB TOTAL	359,000	370,000	355,000	352,000
2. Fixed				
Interest (8%)	130,000	123,000	120,000	118,000
Deprec. (18%)	254,000	241,000	235,000	231,000
SUB TOTAL	384,000	364,000	355,000	349,000
TOTAL ANNUAL	743,000	734,000	710,000	701,000

TOTAL COST SHEET

SURFACE AERATION, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	2,141,000	2,174,000	2,101,000	2,155,000
2. Contingency 15%	321,000	326,000	315,000	323,000
TOTAL INITIAL	2,462,000	2,500,000	2,416,000	2,478,000
ANNUAL COST				
1. O & M				
Electrical	490,000	474,000	408,000	400,000
Oxygen				
Labor	60,000	80,000	120,000	140,000
Parts	43,000	44,000	42,000	43,000
SUB TOTAL	593,000	598,000	570,000	583,000
2. Fixed				
Interest (8%)	197,000	200,000	193,000	198,000
Deprec. (18%)	385,000	391,000	378,000	388,000
SUB TOTAL	582,000	591,000	571,000	586,000
TOTAL ANNUAL	1,175,000	1,189,000	1,141,000	1,169,000

TOTAL COST SHEET

DIFFUSED OXYGEN, PIPELINE, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	980,000	1,049,000	1,084,000	1,218,000
2. Contingency 15%	147,000	157,000	163,000	183,000
TOTAL INITIAL	1,127,000	1,206,000	1,247,000	1,401,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	928,000	860,000	837,000	773,000
Labor	40,000	60,000	80,000	120,000
Parts	20,000	21,000	22,000	24,000
SUB TOTAL	1,018,000	971,000	969,000	947,000
2. Fixed				
Interest (8%)	90,000	97,000	100,000	112,000
Deprec. (6%)	59,000	63,000	65,000	73,000
SUB TOTAL	149,000	160,000	165,000	185,000
TOTAL ANNUAL	1,167,000	1,131,000	1,134,000	1,132,000

TOTAL COST SHEET

DIFFUSED OXYGEN, PIPELINE, 4 mg/l

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	1,094,000	1,161,000	1,286,000	1,356,000
2. Contingency 15%	164,000	174,000	193,000	203,000
TOTAL INITIAL	1,258,000	1,335,000	1,479,000	1,559,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	1,281,000	1,239,000	1,068,000	1,046,000
Labor	60,000	80,000	120,000	140,000
Parts	22,000	23,000	26,000	27,000
SUB TOTAL	1,393,000	1,372,000	1,244,000	1,243,000
2. Fixed				
Interest (8%)	101,000	107,000	118,000	125,000
Deprec. (6%)	66,000	70,000	77,000	81,000
SUB TOTAL	167,000	177,000	195,000	206,000
TOTAL ANNUAL	1,560,000	1,549,000	1,439,000	1,449,000

TOTAL COST SHEET

DIFFUSED OXYGEN, PURCHASE TANK, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	396,000	457,000	447,000	507,000
2. Contingency 15%	59,000	69,000	67,000	76,000
TOTAL INITIAL	455,000	526,000	514,000	583,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	2,784,000	2,562,000	2,255,000	1,861,000
Labor	40,000	60,000	80,000	120,000
Parts	8,000	9,000	9,000	10,000
SUB TOTAL	2,862,000	2,661,000	2,374,000	2,021,000
2. Fixed				
Interest (8%)	36,000	42,000	41,000	47,000
Deprec. (6%)	24,000	27,000	27,000	30,000
SUB TOTAL	60,000	69,000	68,000	77,000
TOTAL ANNUAL	2,922,000	2,730,000	2,442,000	2,098,000

TOTAL COST SHEET

DIFFUSED OXYGEN, PURCHASE TANK, 4 mg/1

	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	617,000	659,000	724,000	760,000
2. Contingency 15%	93,000	99,000	109,000	114,000
TOTAL INITIAL	710,000	758,000	833,000	874,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	4,435,000	4,287,000	3,696,000	3,622,000
Labor	60,000	80,000	120,000	140,000
Parts	12,000	13,000	14,000	15,000
SUB TOTAL	4,537,000	4,410,000	3,860,000	3,807,000
2. Fixed				
Interest (8%)	57,000	61,000	67,000	70,000
Deprec. (6%)	37,000	40,000	43,000	46,000
SUB TOTAL	94,000	101,000	110,000	116,000
TOTAL ANNUAL	4,631,000	4,511,000	3,970,000	3,923,000

TOTAL COST SHEET

DIFFUSED OXYGEN, RENT TANK, 2 mg/l

	SITES	SITES	SITES	SITES
INITIAL COST				
1. Capital	211,000	257,000	272,000	360,000
2. Contingency 15%	32,000	39,000	41,000	54,000
TOTAL INITIAL	243,000	296,000	313,000	414,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	2,784,000	2,562,000	2,255,000	1,861,000
Labor	40,000	60,000	80,000	120,000
Parts	4,000	5,000	5,000	7,000
SUB TOTAL	2,858,000	2,657,000	2,340,000	2,018,000
2. Fixed				
Interest (8%)	19,000	24,000	25,000	33,000
Deprec. (6%)	13,000	15,000	16,000	22,000
SUB TOTAL	32,000	39,000	41,000	55,000
TOTAL ANNUAL	2,890,000	2,696,000	2,381,000	2,073,000

TOTAL COST SHEET

DIFFUSED OXYGEN, RENT TANK, 4 mg/1

	3 SITES	4 SITES	5 SITES	7 SITES
INITIAL COST				
1. Capital	302,000	349,000	428,000	474,000
2. Contingency 15%	45,000	52,000	64,000	71,000
TOTAL INITIAL	347,000	401,000	492,000	545,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	4,435,000	4,287,000	3,696,000	3,622,000
Labor	60,000	80,000	120,000	140,000
Parts	6,000	70,000	9,000	10,000
SUB TOTAL	4,531,000	4,467,000	3,865,000	3,802,000
2. Fixed				
Interest (8%)	28,000	32,000	39,000	44,000
Deprec. (6%)	18,000	21,000	26,000	28,000
SUB TOTAL	46,000	53,000	55,000	72,000
TOTAL ANNUAL	4,577,000	4,520,000	3,920,000	3,874,000

TOTAL COST SHEET

DIFFUSED OXYGEN, PURCHASE PLANT, 2 mg/1

	2 SITES	3 SITES	4 SITES	6 SITES
INITIAL COST				
1. Capital	1,655,000	1,948,000	1,660,000	1,842,000
2. Contingency 15%	248,000	292,000	249,000	276,000
TOTAL INITIAL	1,903,000	2,240,000	1,909,000	2,118,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	804,000	740,000	651,000	579,000
Labor	40,000	60,000	80,000	120,000
Parts	33,000	39,000	33,000	37,000
SUB TOTAL	907,000	869,000	794,000	766,000
2. Fixed				
Interest (8%)	152,000	179,000	153,000	169,000
Deprec. (6%)	99,000	117,000	100,000	111,000
SUB TOTAL	251,000	296,000	253,000	280,000
TOTAL ANNUAL	1,158,000	1,165,000	1,047,000	1,046,000

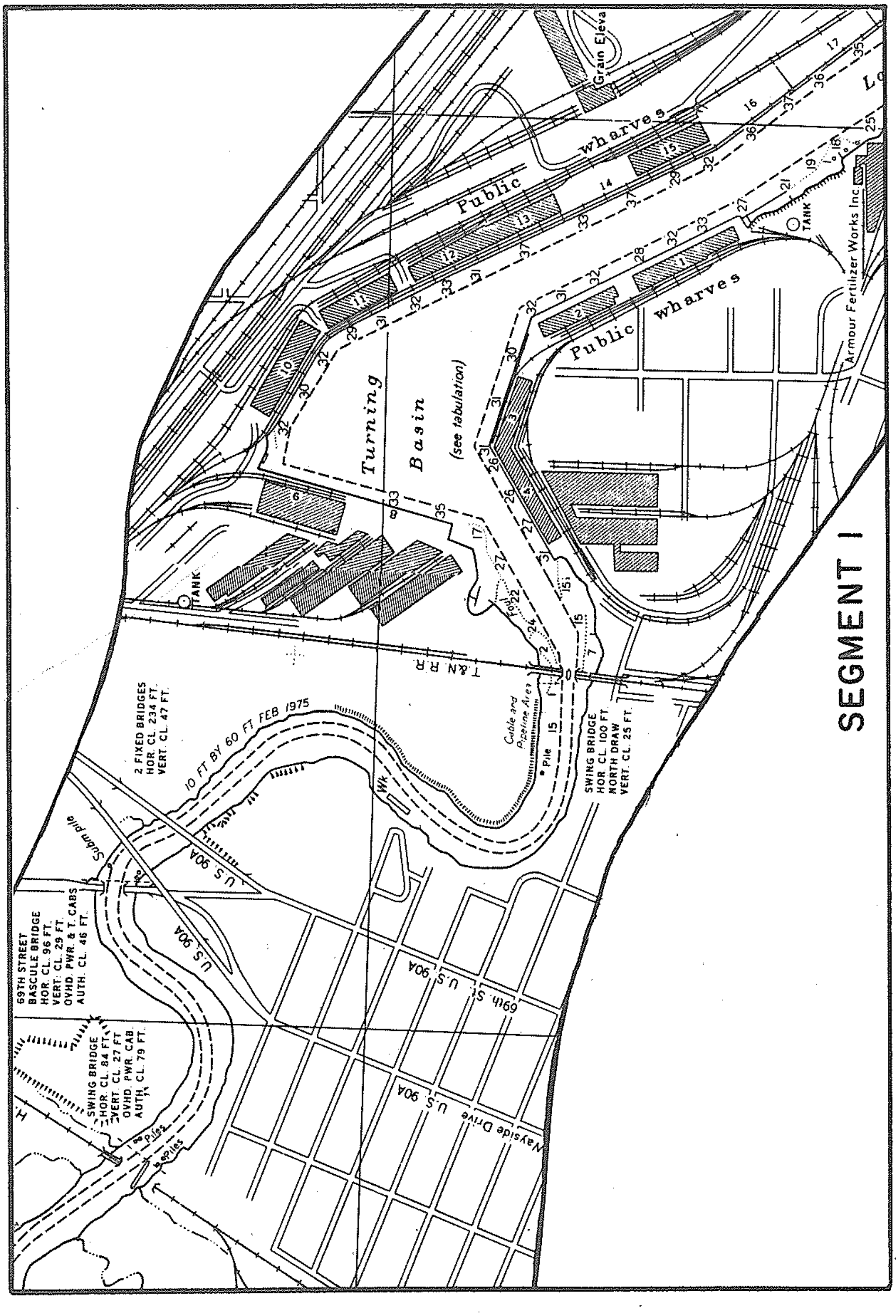
TOTAL COST SHEET

DIFFUSED OXYGEN, PURCHASE PLANT, 4 mg/1

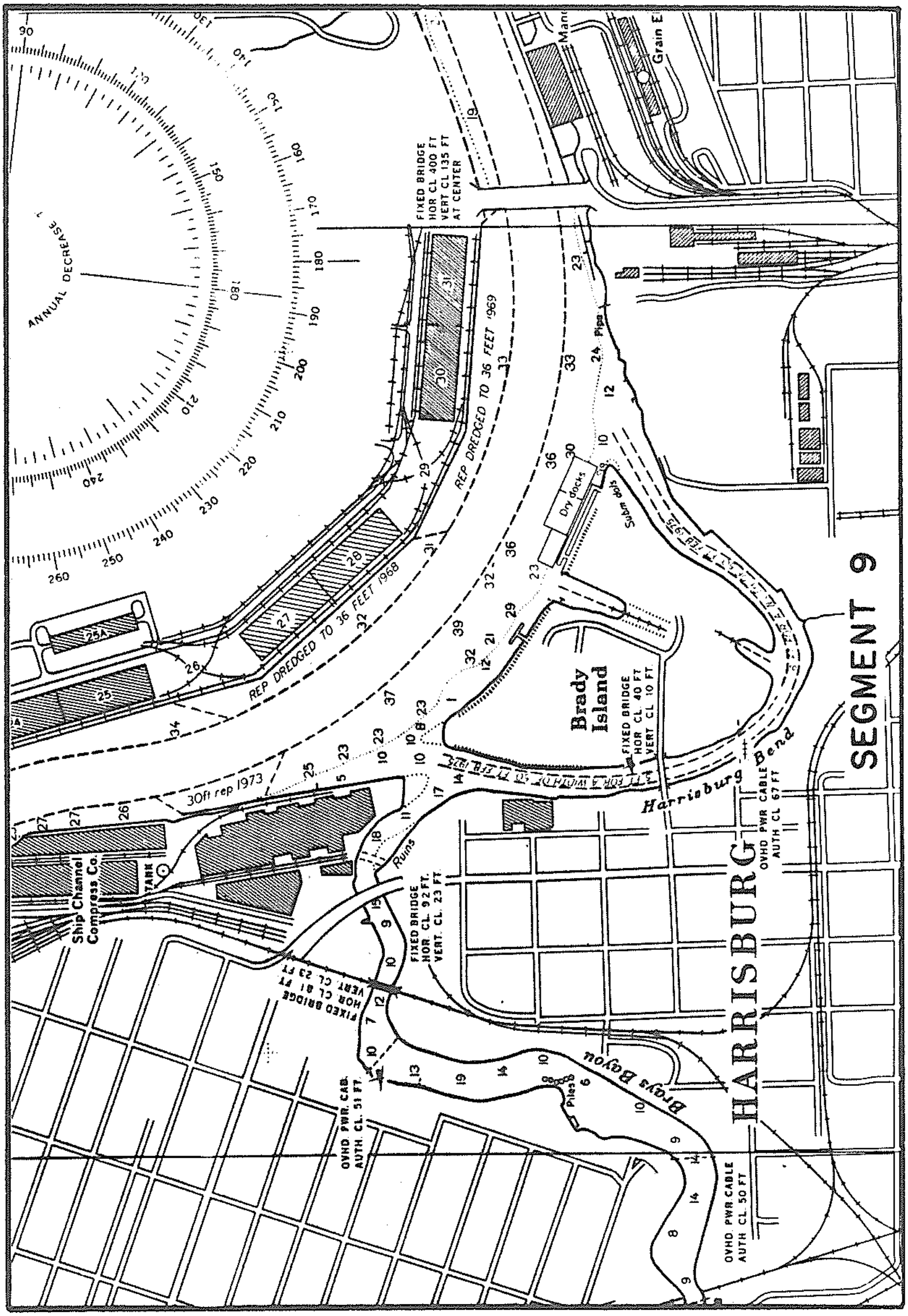
	3 SITES	4 SITES	6 SITES	7 SITES
INITIAL COST				
1. Capital	2,543,000	2,637,000	2,610,000	2,753,000
2. Contingency 15%	382,000	396,000	392,000	413,000
TOTAL INITIAL	2,925,000	3,033,000	3,002,000	3,166,000
ANNUAL COST				
1. O & M				
Electrical	30,000	30,000	30,000	30,000
Oxygen	1,183,000	1,143,000	986,000	966,000
Labor	60,000	80,000	120,000	140,000
Parts	51,000	53,000	52,000	55,000
SUB TOTAL	1,324,000	1,306,000	1,198,000	1,191,000
2. Fixed				
Interest (8%)	234,000	243,000	240,000	253,000
Deprec. (6%)	153,000	158,000	157,000	165,000
SUB TOTAL	387,000	401,000	397,000	418,000
TOTAL ANNUAL	1,711,000	1,707,000	1,595,000	1,609,000

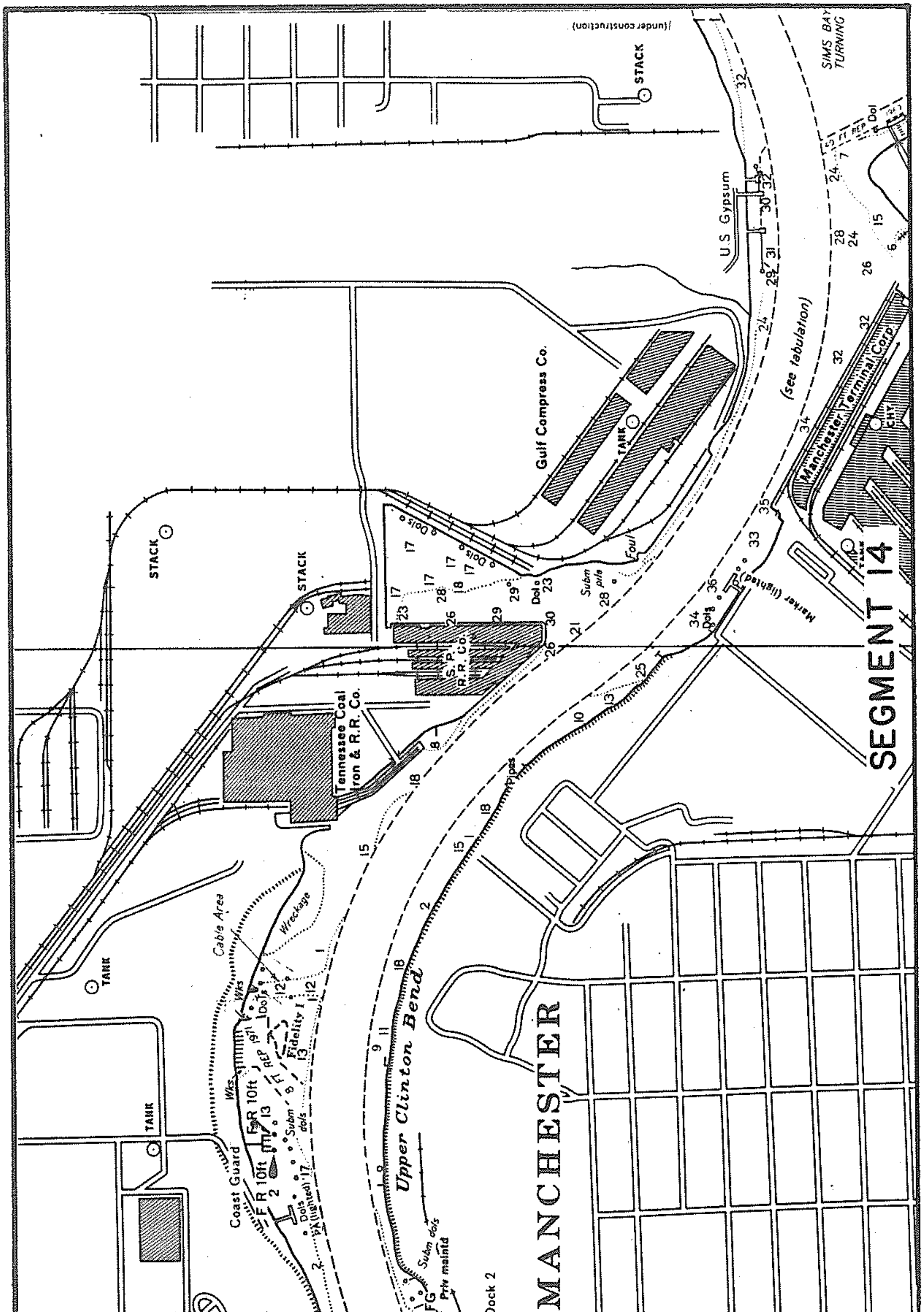
APPENDIX E

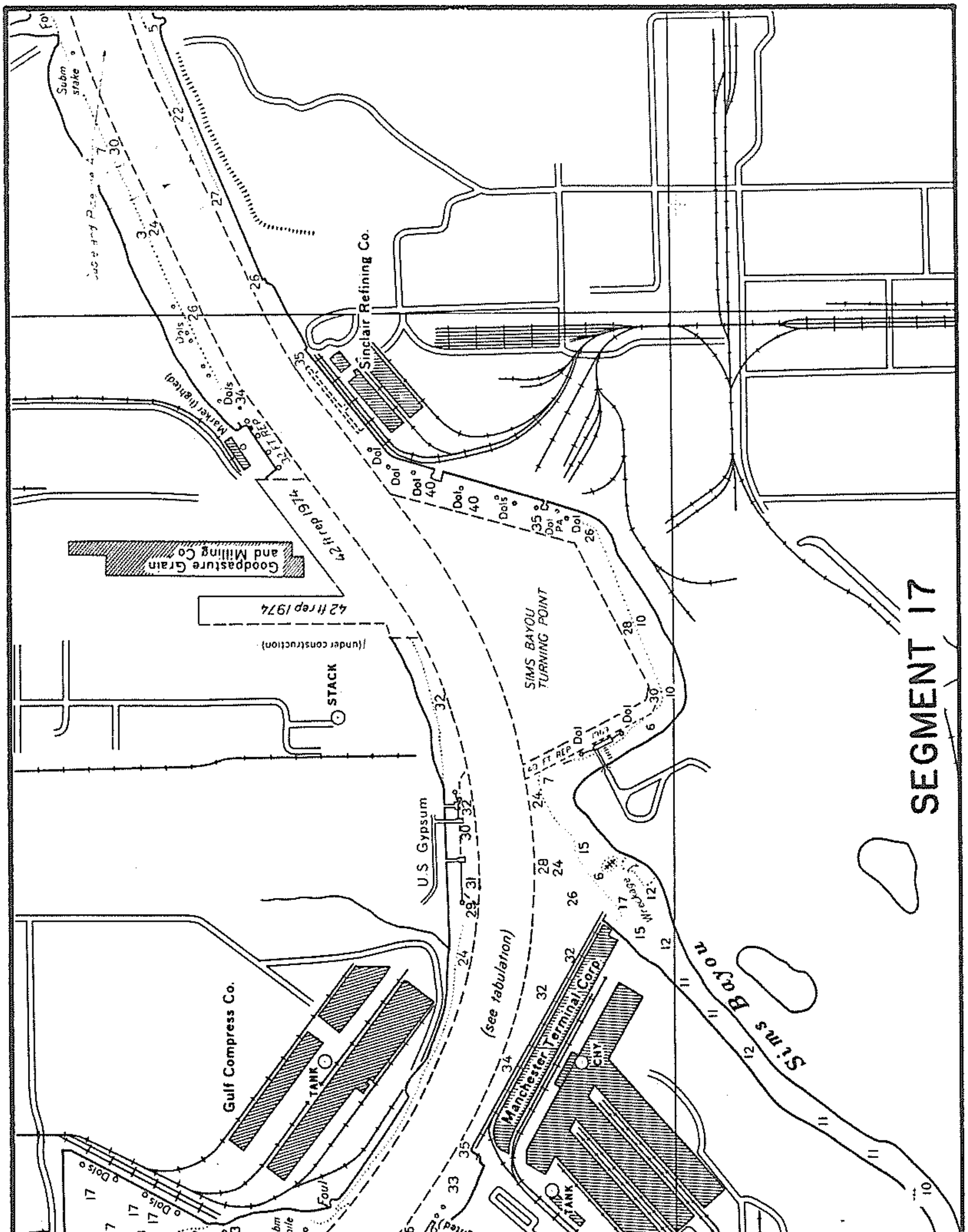
SITE LOCATIONS

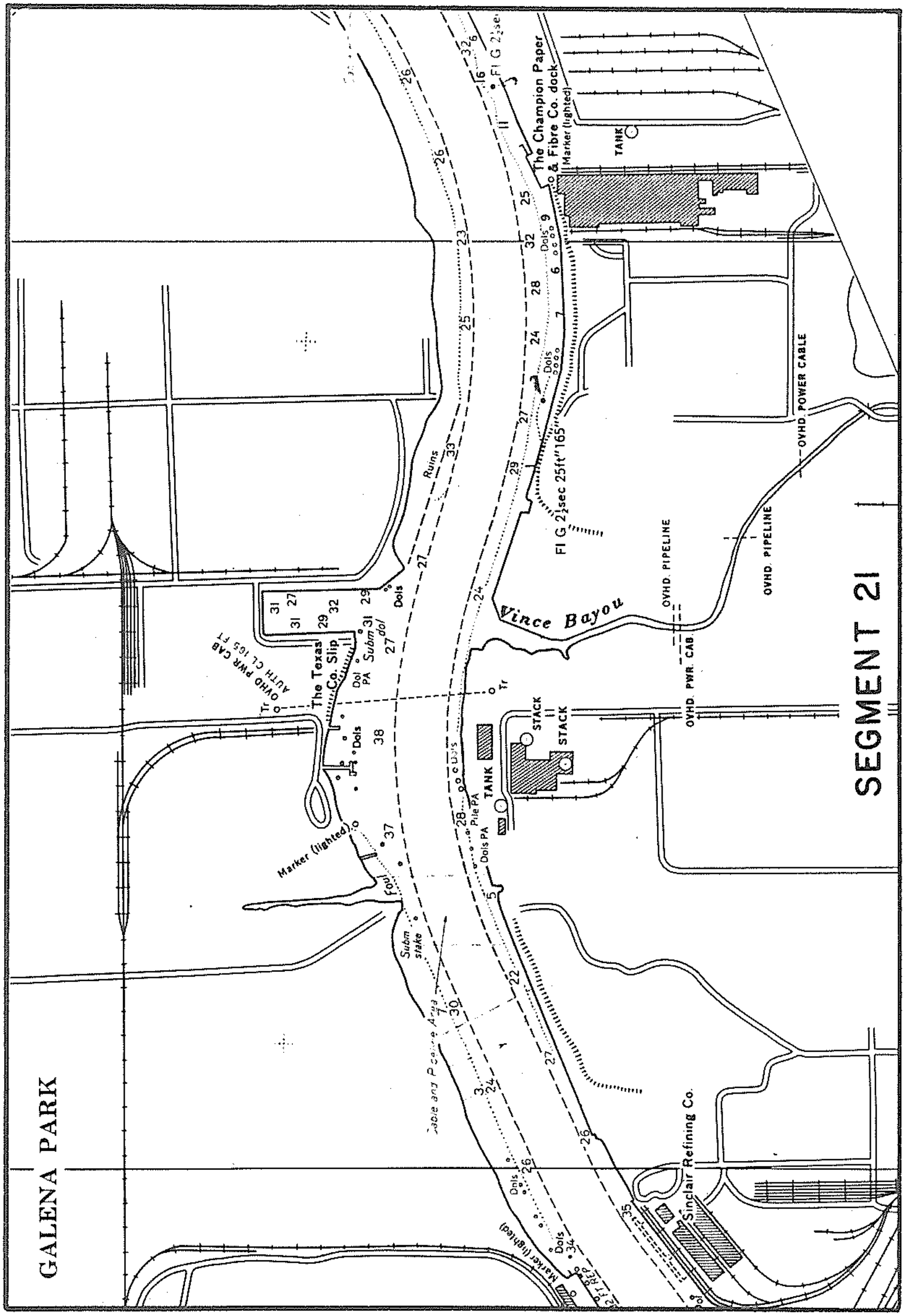


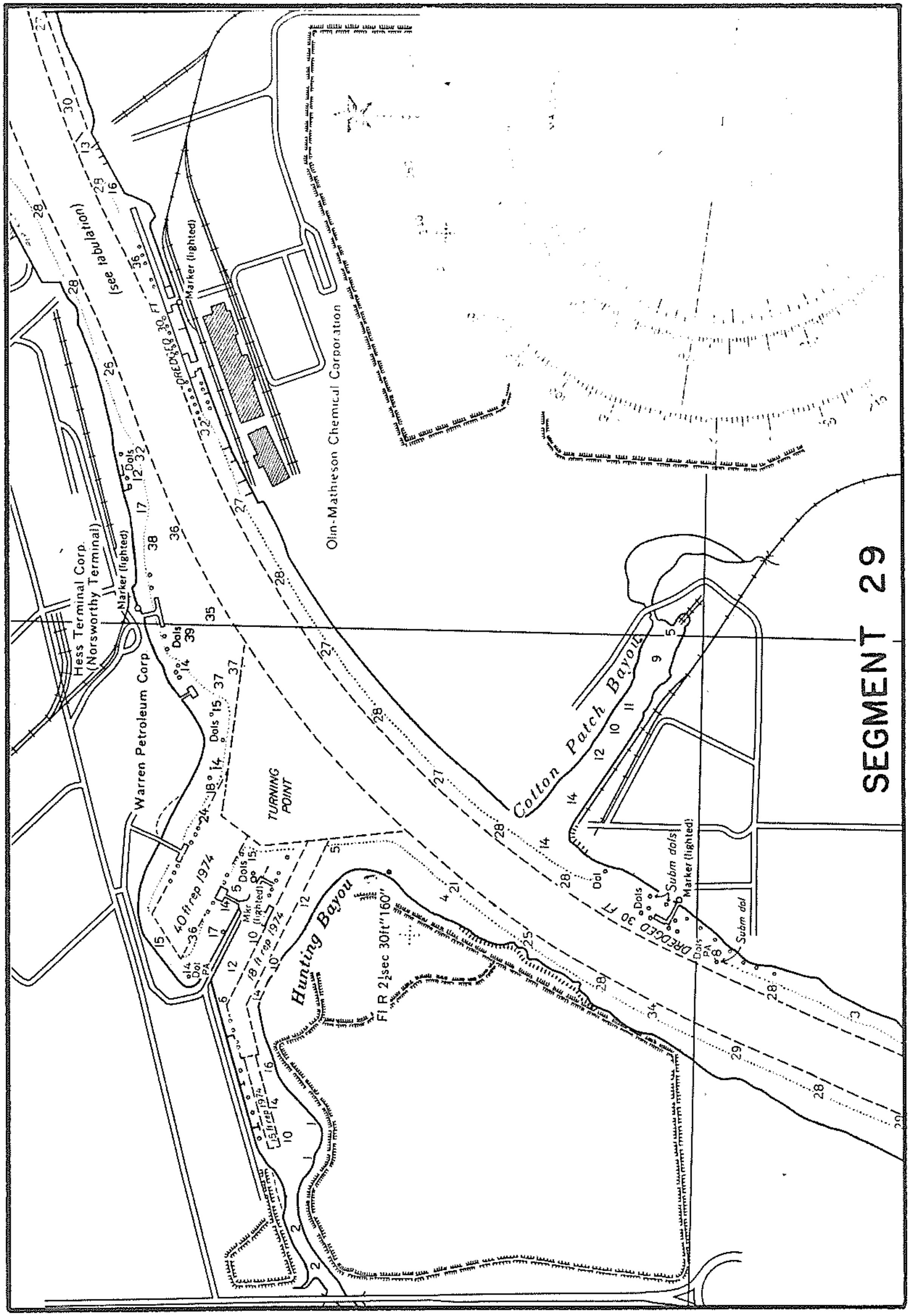
Grain Eleva
Public wharves
Turning Basin
(see tabulation)
Public wharves
Armour Fertilizer Works Inc
TANK
TANK
T.&N. R.R.
Cable and Pipeline Area
Pile
SWING BRIDGE
HOR. CL. 100 FT.
NORTH DRAW
VERT. CL. 25 FT.
2 FIXED BRIDGES
HOR. CL. 234 FT.
VERT. CL. 47 FT.
10 FT BY 60 FT FEB 1975
Subm pile
U.S. 90A
U.S. 90A
69TH STREET
BASCULE BRIDGE
HOR. CL. 96 FT.
VERT. CL. 29 FT.
OVHD. PWR. & T. CABS
AUTH. CL. 46 FT.
SWING BRIDGE
HOR. CL. 84 FT.
VERT. CL. 27 FT
OVHD. PWR. CAB.
AUTH. CL. 79 FT.
Piles
Piles
69th St. U.S. 90A
Wayside Drive U.S. 90A
SEGMENT I

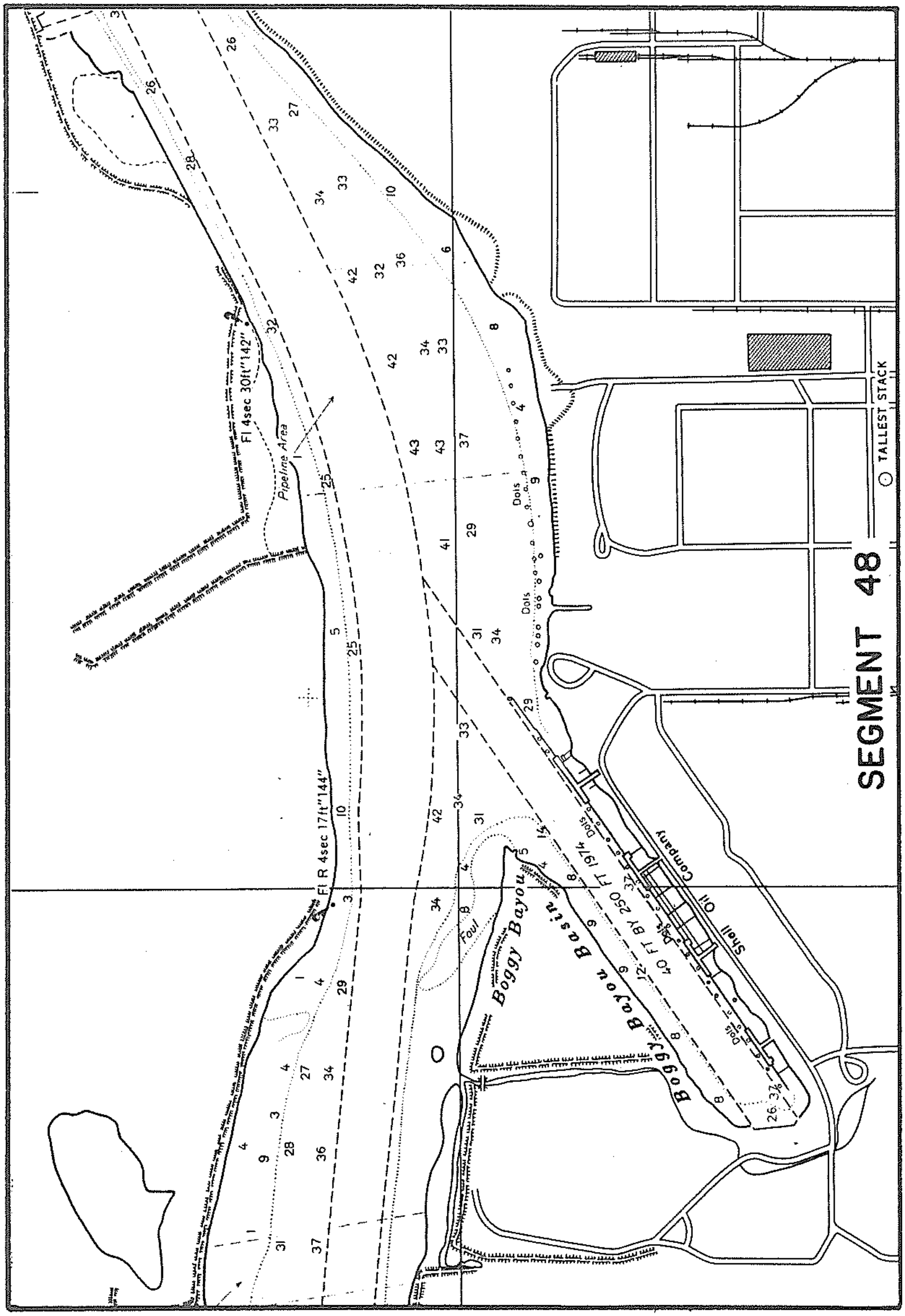

ANNUAL DECREASE
FIXED BRIDGE HOR CL 400 FT VERT CL 135 FT AT CENTER
REP DREDGED TO 36 FEET 1969
REP DREDGED TO 36 FEET 1968
Pipe
Dry docks
Subm dols
Brady Island
FIXED BRIDGE HOR CL. 40 FT. VERT CL. 10 FT.
30ft rep 1973
Harrisburg Bend
SEGMENT 9
OVHD PWR CABLE AUTH CL 67 FT
HARRISBURG
Ship Channel Compress Co.
TANK
Ruins
FIXED BRIDGE HOR. CL. 92 FT. VERT. CL. 23 FT.
FIXED BRIDGE HOR. CL. 81 FT VERT. CL. 23 FT
OVHD. PWR. CAB. AUTH. CL. 51 FT.
Brays Bayou
Piles
OVHD. PWR CABLE AUTH CL. 50 FT


SEGMENT 14
MANCHESTER
Upper Clinton Bend
Tennessee Coal Iron & R.R. Co.
S.P. R.R. Co.
Gulf Compress Co.
Manchester Terminal Corp.
U S Gypsum
SIMS BAY TURNING
(see tabulation)
Marker (lighted)
(under construction)
Coast Guard
Fidelity I
Cable Area
Wreckage
STACK
TANK
Dock 2


SEGMENT 17
Sinclair Refining Co.
Goodpasture Grain and Milling Co
42 ft rep 1974
(under construction)
STACK
SIMS BAYOU TURNING POINT
U.S. Gypsum
Gulf Compress Co.
TANK
(see tabulation)
Manchester Terminal Corp.
Sims Bayou
Marker (lighted)
Subm pile
Foul
S.P. R.R. Co.
Subm stake


GALENA PARK
SEGMENT 21
Vince Bayou
The Texas Co. Slip
The Champion Paper & Fibre Co. dock
Sinclair Refining Co.
OVHD PWR CAB AUTH CL 165 FT
OVHD. PIPELINE
OVHD. PIPELINE
OVHD. POWER CABLE
OVHD. PWR. CAB.
STACK
STACK
TANK
TANK
Ruins
Marker (lighted)
Marker (lighted)
Marker (lighted)
Fl G 2½sec 25ft"165"
Subm stake
Foul
Dols


SEGMENT 29
Olin-Mathieson Chemical Corporation
Hess Terminal Corp.
(Norsworthy Terminal)
Warren Petroleum Corp
Cotton Patch Bayou
Hunting Bayou
TURNING POINT
DREDGED 30 FT
(see tabulation)
Marker (lighted)
Subm dols
Subm dol
Fl R 2½sec 30ft "160"
40 ft rep 1974
18 ft rep 1974
15 ft rep 1974


SEGMENT 48
Shell Oil Company
Boggy Bayou
Boggy Bayou Basin
12 FT 1974
40 FT BY 250
TALLEST STACK
Pipeline Area
Fl 4sec 30ft"142"
Fl R 4sec 17ft"144"
Foul
Dols

APPENDIX F

PRESSURE DROP THROUGH DISCHARGE HEADER

Headloss through a pipe with equally space orifices is given by:

$$h_L = \frac{s_0 l}{3}$$

where:

l = length

$s_0 = KQ^2$

$K = 1/C^2A^2R$

C = the Chezy roughness coefficient

For 4000 gpm, 14-inch diameter, 29 ft. length, C = 118:

h_L = 0.08 psig

For 3500 gpm, 12-inch diameter, 26 ft. length, C = 118:

h_L = 0.10 psig

Where:

l = length

h_L = headloss

s_0 = slope of the energy gradeline without orifices

A = cross-sectional area of the pipe

R = hydraulic radius

APPENDIX G

FINAL COST ANALYSIS

CAPITAL COST

Pump Cost

Purchase cost of pumps in the 3,500 to 4,000 gpm range is \$1.00/gpm (60,61). Installation cost is 100 percent of purchase cost (61). For specifications, refer to text Table 7.4.

Site	Purchase Cost per Pump		Purchase Cost per Pump Station		Installed Cost per Pump Station	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	4000	4000	12000	24000	24000	48000
17	4000	4000	24000	24000	48000	48000
29	3500	4000	7000	24000	14000	48000
				Total	86000	144000

Pump Drive Motor Cost

Purchase cost of 3 phase-60HZ squirrel cage induction motors in the 300-400 HP range is \$25/HP (60,61). Installation cost is 100 percent of the purchase cost (61). For specifications refer to text Table 7.5.

Site	Purchase Cost per Motor		Purchase Cost per Pump Station		Installed Cost per Pump Station	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	8750	8750	26250	52500	52500	105000
17	8750	8750	52500	52500	105000	105000
29	7500	8750	15000	52500	30000	105000
				Total	187500	315000

CAPITAL COST—CONTINUED

Sump Cost

In place concrete cost is $175 to $200 a cubic yard for normal installations. The sheet pile daming and pumping required at this installation increases the cost to $350 a cubic yard. Piling cost is estimated as 200 ft. of piling per pump at $3.50 per foot. The trash rack is estimated at $500 a linear foot. For specifications refer to Figure 7.8.

Site	Concrete Cost		Piling Cost		Trash Rack		Total	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	5390	7245	2100	4200	4500	9000	11990	20445
17	7245	7245	4200	4200	9000	9000	20445	20445
29	4445	7245	1400	4200	3000	9000	8845	20445
						Total	41280	61335

Oxygen Compressor Cost

The purchase cost of a reciprocal positive displacement compressor and drive motor is $125/HP (60,61). Installation cost is 100 percent of the purchase cost. For specifications refer to Table 7.8.

Site	Purchase Cost			Installed Cost	
	2 mg/1	4 mg/1		2 mg/1	4 mg/1
1	6250	12500		12500	25000
17	12500	12500		25000	25000
29	5000	12500		10000	25000
			Total	47500	75000

CAPITAL COST-CONTINUED

PSA Oxygen Plant Cost

The capital cost of PSA oxygen plants is given in Figure 6.2 and the specifications of the required plants are given in Table 7.7. A 40 x 30 foot slab one foot thick at $175 per yard is provided.

Site	Unit Cost		Slab Cost		Total Cost	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	400000	500000	7800	7800	407800	507800
17	500000	500000	7800	7800	507800	507800
29	300000	500000	7800	7800	307800	507800
				Total	1223400	1523400

Oxygen Pipeline Cost

The cost of extending existing oxygen pipeline is estimated at $100,000 per mile (9,61) and the required length is 8.0 miles. The total capital cost of an oxygen pipeline is $800,000.

Eductor Nozzel Cost

Penberthy eductor nozzels three inches in diameter and made of brass cost $200 each (61,60). Installation cost is 100 percent of the purchase cost.

Site	Purchase Cost		Installation Cost		Total Cost	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	11400	22800	22800	45600	34200	68400
17	22800	22800	45600	45600	68400	68400
29	6800	22800	13600	45600	20400	68400
				Total	123000	205200

CAPITAL COST-CONTINUED

Valve Cost

The valve requirements per site are as follows:

a. one manually operated globe valve, diameter equal to the contactor diameter

b. one swing check valve per pump, diameter equal to the lateral diameter

c. one gate valve per distributor lateral, diameter equal to the lateral diameter and installation

The purchase cost of each is taken from "Pump and Valve Selector" (73) and updated Engineering News Record cost index (60).

Swing Check Valves:

Site	Unit Cost		Unit Installation Cost		Total Site Cost	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	1875	1875	125	125	6000	12000
17	1875	1875	125	125	12000	12000
29	1625	1875	125	125	3500	12000
				Total	21500	36000

Globe Valves:

Site	Unit Cost		Unit Installation Cost		Total Site Cost	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	6250	12500	187	250	6437	12750
17	12500	12500	250	250	12750	12750
29	3750	12500	137	250	3887	12750
				Total	23074	38250

CAPITAL COST-CONTINUED

Gate Valves:

Site	Unit Cost		Unit Installation Cost		Total Site Cost	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	1875	1875	125	125	6000	12000
17	1875	1875	125	125	12000	12000
29	1625	1875	125	125	3500	12000
				Total	21500	36000

Piping Cost

Collection header and distributor piping is estimated at \$15/in.-ft. (diameter-length) and contactor piping at \$6/in.-ft. Both values are modified from estimates given by Olszewski (60).

Site	Collection Header		Distributor		Contactor		Total	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	2600	6600	8400	12600	74000	110400	85000	129600
17	6600	6600	12600	12600	110400	110400	129600	129600
29	1500	6600	6000	12600	55900	110400	63400	129600

Control Building Cost

The cost of a metal control building for the electrical power equipment is estimated at \$4,500 per site, \$13,500 total, as indicated in Chapter VI.

Electrical Supply Equipment Cost

Also as indicated in Chapter VI, electrical power equipment is estimated at \$15,000 per site, \$45,000 total.

CAPITAL COST-CONTINUED

Site Preparation Cost

Site preparation includes grading and fencing and is estimated at $14,000 per site, $42,000 total.

OPERATION AND MAINTENANCE COST

Electrical Power Cost

Electrical power is needed for oxygen generation and compression, and water pumps. The cost of power used in oxygen generation is included in the cost of oxygen and not calculated here. Oxygen compression cost and pumping cost are figured at 2 cents per kilowatt hour and 60 percent average operating capacity. For horsepower requirements refer to Table 7.5 and 7.8.

Site	Annual Power Cost	
	2 mg/1	4 mg/1
1	115600	231300
17	231300	231300
29	67300	231300
Total	314200	693300

Oxygen Cost

The cost of oxygen is given on Figure 6.4 and the average oxygen requirements are given on Table 7.7.

Site	Annual Oxygen Cost	
	2 mg/1	4 mg/1
1	77400	95100
17	95100	95100
29	31900	95100
Total	204400	285300

Labor Cost

Operator salaries are estimated at $20,000 per site per year, $60,000 total.

OPERATION AND MAINTENANCE COST-CONTINUED

Replacements Parts Cost

Replacement part cost is estimated at 2 percent per year of the purchase cost of mechanical equipment (i.e. excluding pump sump, piping, and site preparation cost).

Site	Part Cost (PSA O_2 supply)		Part Cost (pipeline O_2 supply)	
	2 mg/1	4 mg/1	2 mg/1	4 mg/1
1	10500	13700	2500	3700
17	13700	13700	3700	3700
29	8000	13700	2000	3700
Total	32200	41100	8200	11100